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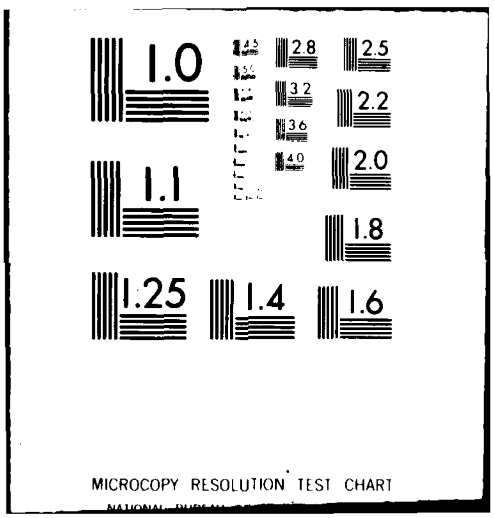
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RESEARCH AND DEVELOPMENT TECHNICAL REPORT
CECOM–81–0006–F

EVALUATION OF RADIATED EMISSION AND SUSCEPTIBILITY MEASUREMENT TECHNIQUES

By

E. E. Donaldson, J. A. Woody, and J. K. Daher

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JANUARY 1982

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The objective of this program was to evaluate current radiated emission and susceptibility measurement techniques to determine their applicability to performing measurements required under MIL-STD-462. To accomplish this objective, program efforts were directed to a review and comparison of the technical capabilities and limitations of current radiated emission and susceptibility measurement techniques and to the identification of voids and deficiencies in current measurement methodologies.

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From the results of this program, it is concluded that a number of measurement techniques offer the potential of serving as viable alternates to those measurement techniques currently employed to satisfy the measurement requirements of MIL-STD-462. However, many of these alternate techniques have as yet not been reduced to practice. A more significant conclusion which is drawn from the program activities and results is that serious deficiencies exist in current EMC/EMI radiated measurement methodologies. These deficiencies include shortcomings in current measurement techniques as well as problems with the overall measurement philosophy dictated by MIL-STD-462.

Shortcomings in current measurement techniques include (1) deficiencies which prevent the maximum utilization of available measurement techniques, (2) deficiencies in reducing to practice those measurement techniques which have been identified as possible alternates to current techniques, and (3) deficiencies related to the lack of correlation of measurement results obtained with different techniques.

From a conceptual or philosophical viewpoint, the MIL-STD-460 series is considered inadequate for practical system EMC control. The use of these standards to ensure that system EMC design limits have been met is questionable since different results can be obtained with different measurement techniques. The inability to relate the measurement results obtained under these standards to the EMC potential of a deployed system represents a relatively ineffective and costly underutilization of the standards.

It is recommended that actions be taken to improve and reduce to practice those measurement techniques which are applicable to the conduct of radiated emission and susceptibility measurements. In conjunction with these actions, a review and update of the overall measurement philosophy and approach to performing radiated measurements should be undertaken to ensure that the measurement techniques employed and the results obtained have maximum applicability to the EMI control of operational systems. Measurement limits to be dictated by the standards should also be reviewed to ensure that these limits conform to the state-of-the-art in EMC/EMI design techniques and in EMC/EMI instrumentation capabilities.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FOREWORD

This final report was prepared by the Engineering Experiment Station at Georgia Tech under Contract No. DAAK80-81-K-0006, Georgia Tech Project No. A-2819. The report summarizes the project activities and results during the period of the contract, from 1 November 1980 through 31 October 1981. The work described in the report was directed by Mr. E. E. Donaldson, Project Director, under the general supervision of Mr. H. W. Denny, Chief of the Electromagnetic Compatibility Division.

1.0 INTRODUCTION

1.1 Program Objective and Scope

This report describes the research activities performed during the period of 1 November 1980 through 31 October 1981 under Contract No. DAAK80-81-K-0006, "Evaluation of Radiated Emission and Susceptibility Measurement Techniques". The basic objective of this program was to determine if current radiated emission and susceptibility measurement techniques are applicable or can be modified in a manner to make them applicable for use in MIL-STD-462. To accomplish this objective, program efforts were directed to three basic tasks:

(1) A review and characterization of current radiated emission and susceptibility measurement techniques in terms of technical capabilities and limitations,

(2) A comparative analysis and categorization of techniques in terms of their applicability as alternate techniques for MIL-STD-462 type measurements, and

(3) A determination of measurement technique deficiencies and appropriate actions which should be taken to address these deficiencies.

It should be emphasized that while the program objective was oriented to the use of MIL-STD-462 as a baseline or reference for the comparison of different measurement techniques, program efforts were not restricted solely to this objective. The program results should permit a comparison of the advantages and limitations of the various measurement techniques irrespective of this military standard. Furthermore, it is also important to recognize that investigations of alternate radiated emission and susceptibility measurement techniques should not necessarily be constrained to those techniques which conform to the current MIL-STD-462 measurement approach, but rather should include those techniques which could offer a more reliable, efficient, or cost effective replacement for the techniques currently employed.

1.2 Background

The achievement of electromagnetic compatibility (EMC) in electronic systems is highly dependent upon the availability of accurate and reliable measurement techniques for defining and controlling electromagnetic interference (EMI) characteristics. Measurements performed at appropriate times and levels (i.e., device, equipment, subsystem, system level) during the design and development of a system are not only necessary to assure that system EMC requirements are met, but are highly cost effective in that they can prevent costly after-the-fact redesigns. The importance of EMC measurements is underscored by the fact that EMC performance requirements are normally imposed in the form of test specifications or standards (MIL-STD-460 series) which delineate the methodology for performing EMI measurements as well as EMI limits which must not be exceeded. The measurement methodology specified by these standards evolved from numerous investigations of EMI measurement techniques, and is an accepted approach to measuring EMI characteristics. However, over the last decade, considerable effort has been directed to the development of improved EMI measurement techniques. In particular, emphasis has been placed on test methods for performing radiated emission and susceptibility measurements. From these efforts, several different measurement techniques for performing radiated emission and susceptibility measurements have evolved, each of which has certain merits and limitations depending upon its application. For example, radiated susceptibility measurements may be made using an anechoic chamber, TEM cell, parallel-plate transmission line, stirred mode shielded enclosure, and other measurement methods.

The availability of the different radiated emission and susceptibility measurement techniques raises a fundamental question - are the techniques applicable, or can they be modified in a manner which will make them applicable for use in satisfying the test requirements of current military standards, i.e., MIL-STD-462? The availability of different techniques which satisfy the requirements of this standard would enable measurement requirements to be met in the most efficient and cost effective manner via the selection of the "simplest" technique for a given application.

To answer the above question, the specific capabilities and limitations of the different measurement techniques must be defined, criteria (relative cost, accuracy, complexity, test time, etc.) for comparing the different techniques must be established, and a comparison of the techniques must be performed to enable the identification of the "best" technique(s) for a given application. Also, where possible, modifications which would increase the capability of a given technique or enhance the compatibility of the different techniques must be identified. Finally, where deficiencies or voids are identified in current radiated measurement methodologies, research and development programs must be defined to address these deficiencies and voids.

1.3 Report Summary and Organization

The material which follows in this report is divided into five major sections, Sections 2 through 6. Section 2 reviews the radiated emission and susceptibility measurement techniques identified in MIL-STD-462. Section 3 provides a detailed characterization of the technical merits and limitations of measurement techniques which are currently available for performing radiated emission and susceptibility measurements. Section 4 provides a comparative analysis of the different measurement techniques in terms of defined parameters, and discusses the applicability of the techniques as alternates to those specified in MIL-STD-462. Section 5 discusses voids and deficiencies which exist in the state-of-the-art of radiated measurement methodologies, and Section 6 presents the program conclusions and recommendations.

2.0 REVIEW OF MIL-STD-462 RADIATED MEASUREMENT TECHNIQUES

This section summarizes the results of a review of the radiated test techniques and test conditions which are identified in MIL-STD-462. A knowledge of these test techniques and conditions is necessary to the identification of radiated emission and susceptibility measurement techniques which might serve as alternate methods for satisfying the test requirements of this standard.

It is first important to note that MIL-STD-462 does not directly specify, require, or recommend any particular measurement technique (i.e., anechoic chamber, shielded enclosure, parallel plate structure, etc.) for performing radiated emission or susceptibility measurements. Rather, the standard specifies that the ambient electromagnetic environment level (with the unit under test deenergized) of the test site shall be at least 6 dB below the allowable specified test limit. Thus it would appear that any radiated measurement technique which met this test condition would be satisfactory. On the other hand, the standard strongly implies the use of certain measurement techniques simply through references to, or descriptions of, these techniques. The standard implies that the use of a shielded enclosure is an acceptable approach to the performance of radiated tests through (1) frequent references (in the text and in figures depicting test set ups) to shielded enclosures or screen rooms, and through (2) the mention of the use of RF absorber material for reducing reflections from surfaces of the enclosure. The standard also refers to the use of the parallel plate transmission line and the long wire antenna for radiated tests over the 14 KHz to 30 MHz frequency range. Thus, for the purposes of this program, these three measurement techniques were used as a reference for the investigation of alternate radiated measurement techniques.

Although MIL-STD-462 identifies the above three techniques as a means of collecting radiated EMC/EMI data, it is important to recognize that these three techniques have limitations which are not clarified in the standard. In fact, the standard is ambiguous in that the lack of guidelines or criteria for the use of the parallel plate, long wire antenna, and shielded enclosure could lead to the misuse of these measurement techniques. For instance, the frequent reference to the shielded enclosure could lead the unknowledgable user to assume that radiated measurements performed in shielded enclosures would provide valid results over the 10 KHz to 40 GHz frequency range. This is obviously not true except for those frequencies where standing waves can not exist (below approximately 20 MHz for an 8 ft. x 8 ft. x 20 ft. enclosure). Furthermore, the standard implies that the use of RF absorber material to reduce reflections is arbitrary, which is incorrect. At those frequencies where reflections/standing waves occur, absorber material must be used to obtain valid measurement results.

Since the combination of a shielded enclosure and RF absorber material (appropriately used) is in essence a shielded anechoic chamber, it was assumed for this program that MIL-STD-462 implies the use of (1) an anechoic chamber for those frequencies where reflections from the enclosure walls are a problem, and (2) a shielded enclosure for those frequencies where reflections/standing waves do not exist within the enclosure. This assumption was necessary to the investigation of alternate measurement techniques since it is obviously not logical to search for an alternate to a shielded enclosure measurement approach which is not valid.

Another factor which must be considered in evaluating or comparing different radiated measurement techniques is the degree of correlation of measurement results obtained with the different techniques. For instance, if measurements on the same system are performed with the shielded enclosure, parallel plate line, or long wire antenna, will the measurement data be the same? Since the characteristics of the electromagnetic field and the interaction between the field and the test specimen is likely to be different for the three measurements, the likelihood of identical test data is questionable. No information has been found in the literature which indicates that the correlation of these (or other) measurement techniques has been investigated.

In conjunction with the above factor, the question arises as to the meaning of MIL-STD-462 data with respect to the interference potential of a system in a operating environment. On the one hand, it is recognized that measurements performed under this standard are not intended to reflect the EMC/EMI performance of a system in any particular environment. On the other hand, given that a system meets its design "limits", it would seem logical that a knowledge of these limits should permit an assessment of whether the system would operate satisfactorily in a given environment. However, the utilization of either of these limits or specific MIL-STD-462 measurement data for this purpose is questionable since the field distributions/levels which exist during MIL-STD-462 measurements will not necessarily correspond to the field characteristics of an operating environment. For instance, suppose that susceptibility measurements were performed on an equipment at 20 MHz in a shielded enclosure (near-field test conditions), and suppose that the equipment just met its test "limit". If the equipment was then deployed in the far-field of a 20 MHz emitter such that it was exposed to a field strength level corresponding to this limit, would interference occur? As a second example, assume that susceptibility measurements were performed on equipment at 20 MHz using the parallel plate structure (simulated far-field test conditions), and then suppose it were deployed in close proximity (near field operating environment) to a 20 MHz emitter. Would the test data permit the potential for interference to be defined? Such questions would be difficult to answer because of differences between the test environment and the operating environment.

The above discussion illustrates a basic problem related to the identification and evaluation of alternate measurement methods for satisfying MIL-STD-462 measurement requirements -- the problem of identifying the specific field distribution characteristics which are required and the interactions which will occur between the field and the equipment under test. This problem was not addressed under this program because of the lack of definitive information which substantiates the differences or similarities between measurement results obtained with the shielded enclosure, parallel plate structure, long wire antenna, and other measurement techniques. Rather, alternate techniques were characterized in terms of such basic measurement parameters as frequency range, accuracy, cost, etc.

It is also to be noted that the use of MIL-STD-462 data only to verify that EMC/EMI design limits have been met is not considered to be a cost effective utilization of measurement results obtained under this standard. The applicability of the results to assessing field interference problems should be determined, and guidelines and criteria should be defined which identifies the utilization of the results for this purpose.

3.0 DESCRIPTION OF MEASUREMENT TECHNIQUES

3.1 Introduction

Various measurement techniques exist which may be applicable as supplementary or alternate methods for satisfying the measurement requirements of MIL-STD-462. In order to determine their applicability and to permit the selection of the most appropriate technique(s), a detailed characterization of each technique in terms of technical capabilities and limitations is required. The first step in characterizing the alternate measurement techniques is to identify each technique and describe each technique in detail.

3.2 Open Field

A "true" open-field test is one technique which can be used to obtain accurate radiated emission and susceptibility data. A true open-field test environment eliminates the adverse effects of nearby objects (such as metal walls, structures, personnel, etc.) and provides a low ambient electromagnetic test environment. That is, a true open field closely simulates the ideal free-space physical and electromagnetic environments appropriate for accurately performing far-field radiated EMI tests. Consequently, it is generally used as the reference environment for comparing radiated measurements made using other techniques.

In practice, however, a true open field is very difficult to achieve, since a large, flat area free of significant reflecting objects and externally generated fields rarely exists. At most practical open-field sites, an externally generated, ambient electromagnetic environment that varies with time is present and must be accurately defined. In general, the ambient environment should be at least 6 dB below the applicable emission limits. It is difficult to locate an open-field site that meets this requirement, especially at HF where field intensities up to 40 dB greater than the emission limits are common in even remote areas.

An open-field test site can be used to perform susceptibility tests only under special circumstances. Susceptibility tests by their nature require the radiation of intense electromagnetic fields. Therefore, care must be exercised to insure that open-field susceptibility tests are performed on a non-interference basis. In fact, FCC approval must be obtained for open-field radiation at discrete frequencies.

Open-field sites are advantageous for testing large systems since they inherently have large test volumes. However,they generally involve high power transmitters (for susceptibility tests) or high sensitivity receivers (for emission tests) because of the large distances between the test sources/receivers and the unit under test. Also, even with low proximity effects from surrounding obstacles, the ground reflections from the earth typically vary with changes in weather conditions and between different test sites. These reflections can reduce the resulting measurement accuracy and necessitate the use of highly skilled operators skills to achieve acceptable accuracy.

Significant improvements in open-field measurement accuracy can be achieved by installing a large metal ground plane at the test site. With a well-defined reflecting surface, the ground reflections can be accurately determined and appropriate correction factors can be applied to the measured data. Thus, the accuracy of the open-field technique can be increased and the site-to-site repeatability can be improved.

Operation of an open-field site must take into account unfavorable weather conditions which can make test scheduling difficult. Varying weather conditions can cause false starts, rescheduling, postponements, and even cancellations of radiated open-field tests. These impediments due to the weather generally result in costly idle time.

Even when weather conditions do not prevent the conduct of open-field measurements, they can significantly influence measurement results. For example, reflections from the ground and other objects (trees, etc.) will be different after a rainfall. Also, at higher frequencies, atmospheric absorption losses will be influenced by weather conditions.

Travel to and from a remote open-field test site can lead to lost time and increased costs. In addition, the expenses associated with procuring and maintaining a sufficiently large open-field site to accomodate far-field radiated tests must be included in the over-all costs. As a result of the above factors and requirements, the performance of radiated emission and susceptibility tests at an open-field test site can be time consuming and expensive.

3.3 Shielded Enclosure

The lack of electrical isolation from the ambient electromagnetic environment is the major technical disadvantage of using an open field test site. To achieve the necessary isolation, most radiated emission and susceptibility tests are currently performed in a shielded enclosure. The shielded enclosure provides a significant degree of isolation between the test configuration and the external environment and thus minimizes both the radiation and reception of undesired signals. Shielding against an EM phenomena is achieved by placing a metal barrier between the test volume and the external environment. The shielding barrier must completely enclose the test volume to provide an adequate degree of isolation. Thus, the shielded enclosure normally has the form of a rectangular room with metallic walls, floor, and ceiling.

Shielded enclosures that provide 100 dB or more of isolation from 10 KHz to greater than 20 GHz are readily available from numerous manufacturers. Typically, enclosures with isolations on the order of 120 dB are available. These commercially available shielded enclosures range in size from small boxes (approximately 2 x 2 x 2 feet) to large rooms (e.g., rooms as large as 40 x 40 x 100 ft. are not uncommon). The minimum size enclosure which is generally acceptable for EMC/EMI testing is 8 x 8 x 8 feet. The dimensions of the enclosure must be sufficient to accommodate the test specimen, the test antennas, and the minimum clearances required between these test objects and the six conducting walls of the enclosure. Alternately, the maximum test specimen size is determined by the dimensions of the shielded enclosure less the required clearances and the required space for personnel.

Typical requirements for clearances between parts of the test setup and the metal walls of the shielded enclosure are 1 meter. Considerations of these clearance requirements, the physical size of some of the test antennas, and other factors indicate that a 15 x 20-foot shielded enclosure 10-feet high is necessary. However, due to economical and space limitations, the most popular size of enclosure is 12 feet wide, 18 feet long, and 8 feet high [1].

The cost of the shielded enclosure is a function of its size as well as the degree of isolation required. The current cost of a shielded enclosure (materials and installation) is approximately \$25 - \$30 per square foot of surface area (walls, ceiling, and floor). Thus, the cost of a medium size enclosure (e.g., 12 x 18 x 8 feet) would be on the order of \$13,000 - \$15,000. In contrast, the cost of larger enclosures (e.g., 40 x 40 x 100 feet) would be in the hundreds of thousands of dollars.

In addition to the isolation that is achieved, a shielded enclosure has several other advantages when compared to the open field. For example, the conduct of tests is not weather dependent, the travel time to and from the test site is minimal, and the overall test time is less since there is normally less lost time due to false starts, rescheduling, and travel.

The major disadvantage of the shielded enclosure for performing radiated emission or susceptibility measurements is its limited frequency range. The specific frequency range over which a given size enclosure will yield accurate measurement results has not been determined; however, experiments performed have indicated that enclosure measurements will duplicate open-field measurements only for frequencies well below the first resonant frequency of the enclosure. For example, coupling measurements performed at 20 MHz and below in an 8 ft. x 8 ft. x 20 ft. enclosure yielded results which were essentially the same as those obtained on an open-field test range [2]. At higher frequencies, where standing wave/multipath effects become pronounced, measurement results obtained in the same enclosure differed as much as 40 dB from open-field test results [2]. The measurement conditions which contribute to such inaccuracies at higher frequencies is illustrated in Figure 1, which depicts signal multipath conditions in a typical shielded enclosure measurement configuration. Although this illustration shows only a fraction of the multiple signal paths that can exist in the shielded enclosure, it is apparent that the total energy arriving at the receiving antenna may be either significantly greater than or significantly less than would be obtained from only the desired signal path. The specific field intensity resulting from all the paths depends on the phases of the signals arriving from the various paths relative to the phase of the signal arriving over the desired path. These relative phases are determined by frequency of the signal and the path length (which is determined by the size of the enclosure, the location of the test setup in the enclosure, and the source to receiving antenna spacing).

3.4 Anechoic Chamber

Several techniques exist for minimizing the errors associated with radiated measurements in shielded enclosures. These techniques involve the simulation of open-field conditions while providing isolation, convenience, and weather protection. Technically, the best technique is to line the interior surfaces of the six metal walls of the shielded enclosure with appropriate RF absorbing material, thus forming a shielded anechoic chamber.

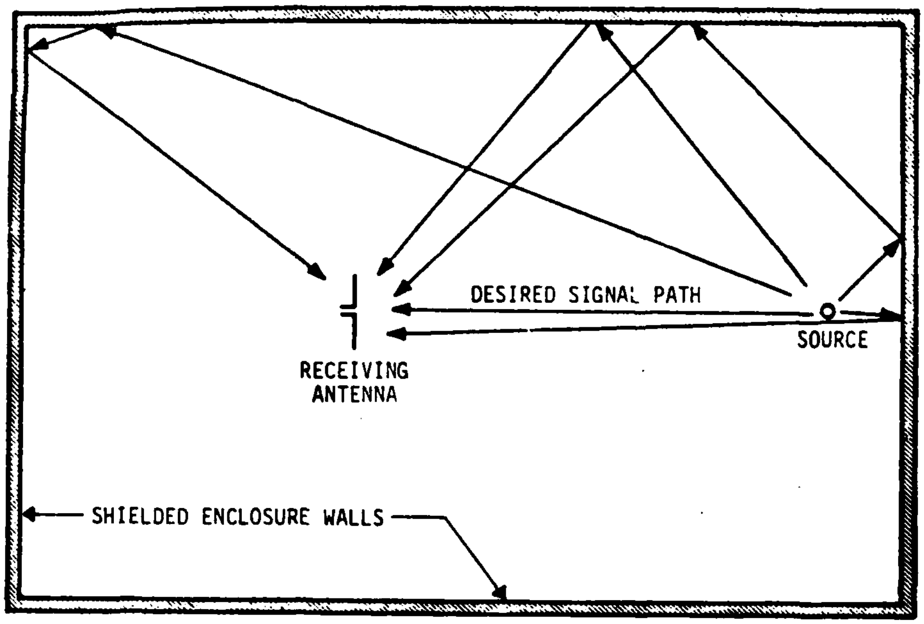

Figure 1. Diagram of a Conventional Measurement Setup in a Shielded Enclosure Showing Multiple Signal Paths.

This type chamber has the same isolation as the equivalent shielded enclosure, yet, by absorbing the radiated energy in the chamber, provides a low reflection test volume in which radiated emission and susceptibility tests can be performed. The test volume, or quiet zone, must be of sufficient size to contain the equipment under test and the reflected energy in the quiet zone should be 20 to 30 dB below the desired path energy. These requirements dictate the physical size of the chamber as well as the characteristics of the RF absorbing material.

In general, for appreciable absorption of radiated energy, the absorbing material should be at least one-quarter free-space wavelength thick. (An exception is ferrite absorbing material which can be considerably smaller; however, its cost is so high - greater than $100 per square foot - that it is generally not considered cost effective in the design of anechoic chambers.) Since wavelength is inversely proportional to frequency, the thickness of the absorbing material must be increased as the frequency of interest drops. For example, absorbing material must be at least 30-in. thick to be effective at 100 MHz and 60-in. thick at 50 MHz. As the thickness of the absorbing material is increased, there are three factors which limit the low-frequency threshold of anechoic chambers: (1) the cost increases; (2) the size of the shielded enclosure must increase to retain the same test volume; and (3) it becomes difficult to mount the material so as to prevent sagging. For these reasons, most existing anechoic chambers have low frequency limits of 200 MHz or higher.

In addition to the low frequency limitations, another disadvantage of shielded anechoic chambers is their relatively high cost. A rule-of-thumb estimate of the cost of shielded anechoic chambers is $30 to $40 per cubic foot of usable test volume for typical laboratory size chambers. Even though the cost per cubic foot of test volume varies with chamber size, the total cost of any size chamber is relatively quite high. In particular, very large chambers often require supplemental supporting structures which add further costs.

The accuracy of measurements performed in a shielded anechoic chamber depends on several test parameters such as:

- the test setup location in the chamber (particularly the distances to the internal surfaces of the chamber)
- the directivity of the antennas used
- the source to receptor separation distance
- the test frequency
- the reflectivity of the absorbing material

Thus, it is not possible to specify the absolute accuracy of anechoic chamber measurements without specifying the test setup in detail. In addition, the measurement accuracy is dependent on the magnitude of the energy being measured relative to the maximum radiated energy in the chamber. The relative accuracy of a typical laboratory anechoic chamber, however, is high when compared to the other measurement techniques. In many instances, it is better than a practical open-field test site and approaches the accuracy of a "true" open-field site.

In summary, the shielded anechoic chamber will permit accurate measurements and provide significant isolation from the electromagnetic and atmospheric environments. The complexity of the measurement procedures and test setup is the same or slightly less than that required in the open field and the total test time and operator skill required is less. On the other hand, it requires a relatively large test facility to test large test samples, which can lead to considerable expense.

3.5 Partial Anechoic Chamber and Hooded Antenna

A second technique used to minimize the errors associated with radiated measurements in a shielded enclosure while reducing the cost relative to an anechoic chamber is the shielded, partial anechoic chamber. This technique involves partially lining the interior walls of a shielded enclosure with absorbing material and then employing a highly directive antenna. The equipment under test is positioned between the antenna and absorbing material. The antenna is oriented such that the majority of the energy radiated strikes the absorbing material, thus reducing multipath reflections and improving measurement accuracy. However, for most antenna types, some radiated energy will still strike the bare metal walls, causing some multipath reflections. The accuracy will, therefore, be less than that of a total anechoic chamber. On the other hand, since only part of the interior walls are lined with absorbing material, the cost will be less than the cost of a total anechoic chamber.

A specific example of a partial anechoic chamber that more closely approximates an anechoic chamber than does other partial anechoic chamber measurement techniques is the hooded-antenna technique. The hooded-antenna measurement approach reduces the measurement errors in a shielded enclosure to a level comparable to those normally encountered in open-field measurements for the 200 MHz to 12 GHz frequency range [2], [3]. The hooded-antenna measurement concept is illustrated in Figure 2. The directive antenna in this technique consists of a test antenna shielded with a metal hood in all but the desired direction. The inside of the hood is lined with absorbing material to reduce reflections from the hood to the test antenna. Also, the enclosure wall opposite the open end of the hood is lined with absorbing material to prevent reflections from this wall to the test antenna. The absorber-lined walls of the hood, together with the one lined wall of the enclosure, look approximately the same to the test antenna as the six absorber-lined walls of an anechoic chamber. The hooded-antenna technique requires significantly less absorbing material, and, consequently, costs less than a total anechoic chamber.

The early experimental investigations of the hooded-antenna concept indicated that the measurement accuracy of this technique is comparable to the accuracy normally achieved with open-field measurements. Two hooded antennas covering the 200 MHz to 12 GHz frequency range were designed, constructed, and evaluated. Each hooded antenna consisted of a balanced log conical antenna inside a cylindrical hood. The hoods were constructed with 1/8-in sheet aluminum and are lined with Eccosorb^{R} NZ-1 ferrite absorbing material. The

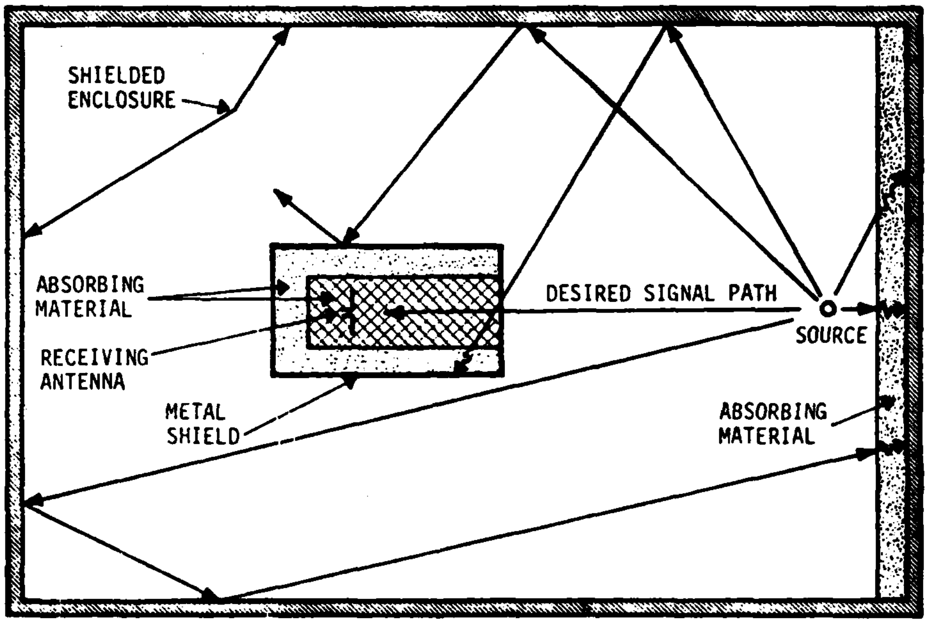

Figure 2. Diagram of a Hooded Antenna Measurement Setup in a Shielded Enclosure.

hoods are fairly large to accomodate the lengths of the log conical type antennas. The UHF hooded antenna (200 MHz to 1.5 GHz) is 24 inches in diameter and 49 inches long and the microwave hooded antenna (1 to 12 GHz) is 8 inches in diameter and 19.5 inches long.

In order to reduce the hood length and, hence, minimize the size, weight, and expense of the hooded antennas, subsequent investigations were conducted using cavity-backed planar log spiral antennas [4], [5]. These investigations indicated that four short hooded antennas could be used to cover the 400-MHz to 12 GHz as follows:

Frequency	Hood Dimensions	
Range (GHz)	Inside Diameter (inches)	Length (inches)
0.4 to 1.0	24	12
1.0 to 2.0	12	4
2.0 to 6.0	4	2
5.0 to 12.0	2	1

Evaluations of these short hooded antennas showed that the resulting measurement accuracies are equivalent to those obtained with the larger hooded antennas (i.e., the errors are 2 to 3 dB).

The hooded antenna radiated measurement technique has all the advantages of the shielded enclosure and the anechoic chamber, plus greatly improved measurement accuracy relative to a shielded enclosure and reduced cost relative to an anechoic chamber. The major disadvantage of this technique is that special test apparatus, i.e., the hoods, must be constructed.

3.6 Mode Perturbation

Another radiated measurement technique used to reduce the measurement errors associated with a shielded enclosure is the mode perturbation technique illustrated in Figure 3. This technique utilizes a movable reflecting surface which significantly improves the energy density uniformity of a shielded enclosure. A radiating source is introduced into the enclosure (radiating antenna in susceptibility measurements or the EUT in emission measurements) and the field is perturbed by rotating the reflector. The goal is to excite as many modes as possible at the test frequency. The likelihood then becomes high that the receiving antenna (or EUT) will be located at a maximum of the standing wave distribution for at least one of the excited modes, and the maximum value should be independent of the antenna (or EUT) position [6]. The required high number of modes restricts the applicability of this technique to frequencies above approximately 100 MHz. The two basic implementations of mode perturbation are the mode-stirred enclosure and the mode-tuned enclosure.

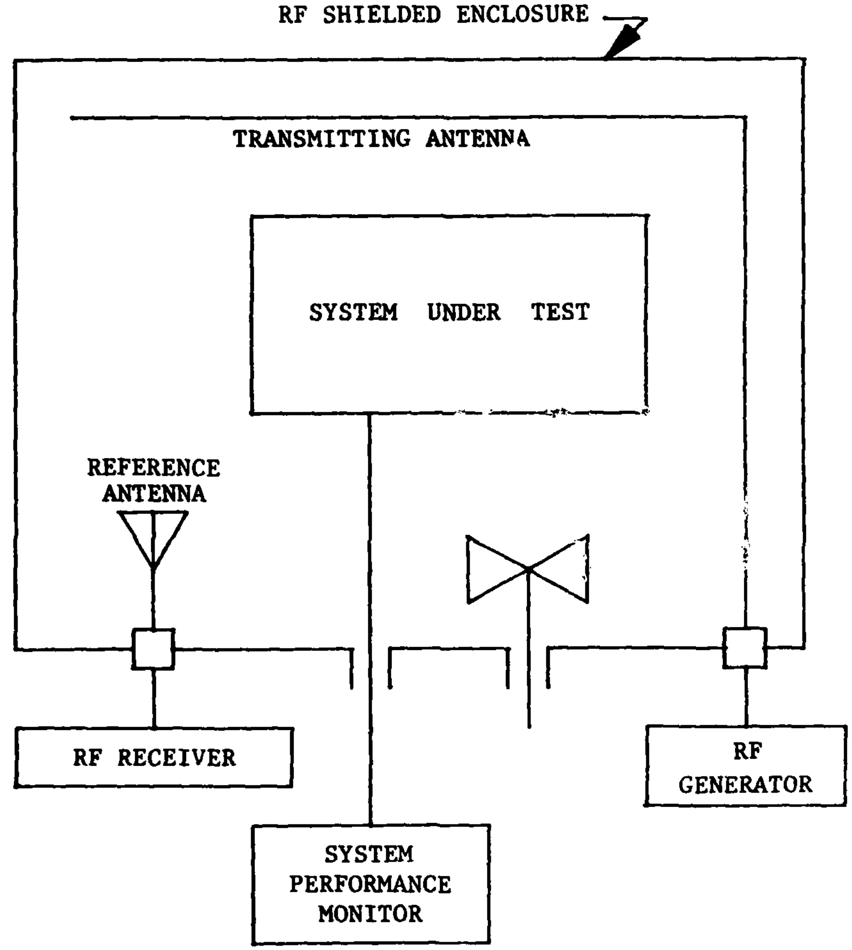

Figure 3. Illustration of Mode Perturbation Measurement Technique.

In the mode-stirred enclosure, one or two large reflecting surfaces are rotated within the enclosure resulting in a combination of modal and spatial perturbation. The electric field incident upon the reference antenna will pass through a maximum value (E_{max}) as the reflecting surface is rotated. Since the losses remain relatively constant, E_{max} will exhibit considerable consistency from mode to mode and its value can be readily measured. The average field intensity (E_{ave}) has also been shown to be quite uniform [7] and either of these quantities may be used for calibrating the fields existing within the enclosure. The electric field intensity (E_{max} or E_{ave}) is related to the power radiated from the source (P_{rad}) by $P_{rad} = k(\omega)E^2$. The function k (ω) should be measured for each shielded enclosure since it is dependent on the Q of the cavity. A procedure for measuring $k(\omega)$ is to use a CW source to drive an omnidirectional antenna, monitor P_{rad} with a directional wattmeter, and record the value of E for each calibration point. A radiated emissions test can then be made by measuring the field at any point in the room (provided the probe is not adjacent to an enclosure wall) and determining the radiated power of the EUT. An approximation to the field intensity (E_o) which would be emitted by the EUT under open field conditions (obtained by assuming hemispheric radiation and far-field conditions) is given by the relation $E_o = \frac{60\, P_{rad}}{R}$ V/m, where P_{rad} is in watts, R is in meters, and E_o is in volts/meter. This method has been tested for a variety of sources and the calculated field intensities based on the enclosure measurements have consistently been within ± 6 dB of open-field values [6]. In radiated susceptibility measurements, the procedure is reversed. The power radiated into the enclosure is monitored while the fields are "stirred" in order to determine the average power density incident upon the device. Good correlation has been obtained between results of measurements made in a mode-stirred enclosure and in an anechoic chamber. Agreement between the two techniques has been shown to be within experimental error [8].

In the mode-tuned enclosure, the reflecting surface is positioned so as to obtain maximum coupling between the EUT and the transmitting or receiving antenna (for radiated susceptibility and emission tests, respectively). Sampling procedures may also be used wherein the reflector is stepped in small increments in order to redistribute the fields around the EUT while coupled signal levels are recorded. The data may then be processed to determine average levels or probability density distributions, if desired.

Questions concerning both stirred-mode and tuned-mode techniques exist, however, which will require additional research efforts for their resolution. One question is concerned with the effect of the closely coupled, shielded environment on the radiated emissions of an EUT as compared with emissions under free space conditions. Another fundamental question involves the differences between coupling to the EUT by the complex enclosure fields versus plane wave coupling in free space. Finally, the upper frequency limit for the two techniques has not been established. It is expected that this limit will depend primarily on the losses in the walls of the enclosure.

Nonetheless, the mode perturbation techniques do offer a number of attractive features. The high degree of coupling between the EUT and the source and/or probe antennas allows for a major reduction in required RF power (which is often a limitation in radiated susceptibility measurements) and,in addition, permits the detection of low level radiated emissions. The system costs are also relatively low compared to open-field or anechoic chamber facilities. The mode perturbation technique can be automated rather easily and test time and manpower requirements may be reduced considerably. In addition, a single worst-case measurement may be performed to determine the maximum emissions or susceptibility without the need for rotating the EUT as required by many other techniques.

3.7 TEM Transmission Lines

A potential difficulty with all radiated measurement techniques which employ antennas inside of an enclosure is the necessity to perform the measurements in the near field. Ideally, the spacings between the enclosure walls, the equipment-under-test, and the antennas should be large enough to minimize interactions and to provide plane-wave fields. Another way of stating this requirement is that far-field conditions are required to obtain accurate results comparable to far-field results measured in the open field. Far-field conditions are not always achievable, however, because of the limited size of the enclosure, the size of the equipment-under-test, the size of the required test antennas, the sensitivity requirements, and/or the necessity for high field intensities during susceptibility testing.

The TEM transmission line measurement technique has been employed to minimize the near-field problems associated with measurements utilizing antennas in an enclosure. With this technique, the equipment-under-test is placed inside a transmission line which supports TEM wave propagation approximating plane-wave electric fields. In effect, the TEM transmission line structure is used to simulate far-field conditions for the equipment-under-test without the use of antennas and without far-field separation distances. These structures include four basic types:

- Parallel plates or strip lines
- Tri-plate lines
- TEM cells
- Long wire antennas

The parallel-plate structure used in the radiated susceptibility test (RS04) in MIL-STD-462 consists of two metal plates which are 24-inches wide, 10-ft. long, and separated by 18 in. This structure can theoretically be used up to the frequency where the plate separation distance is one-half wavelength ($\lambda/2$) i.e., up to the frequency where multimoding can occur. The theoretical upper frequency limit of the MIL-STD-462 parallel plate is, thus, 328 MHz. However, even at frequencies of less than one-half this theoretical limit the structure tends to radiate. For these and other practical reasons the plate-plate structure is typically used only for measurements at frequencies ranging from from dc up to approximately 30 MHz.

Although the lengths of the parallel plates are normally 10 ft. for practical reasons, there is no maximum length under proper impedance-matched conditions. At frequencies where the total length of the lines from the generator through the parallel-plate structure to the load is less than one-tenth wavelength, the structure functions as a large, air-dielectric capacitor whose plates interconnect the source and load. However, if the plate length or the frequency is increased, the parallel plate structure behaves more truly like a transmission line. Hence, any impedance mismatches may result in significant standing waves which reduce the measurement accuracy. This factor limits the maximum practical length as well as the maximum operating frequency.

The parallel plate structure is terminated on each end with matched loads to ensure that it operates in the TEM mode. The plate separation and the width of the plates determine the characteristic impedance of the structure. The impedance of the MIL-STD-462 parallel plate line is 83 ohms. Hence, 83 to 50-ohm matching networks must be used on each end of the structure. A generator is connected to one matching network to drive the line and a 50-ohm receiver or RF voltmeter is connected to the other matching network to measure the voltage (V) between the plates. The magnitude of the field intensity (E) between the plates is given by $E = V/h$, where h is the separation distance between the plates (18 inches for the MIL-STD-462 structure). The equipment-under-test (EUT) is placed between the parallel plates and its operation is monitored for malfunction or degradation of performance.

In addition to simulating far-field conditions and eliminating the need for antennas, the magnitude of the fields which can be generated is another major advantage of the parallel-plate line. This structure can be used to produce field intensities up to several hundred volts per meter with the only practical limitation being the power ratings of the matching networks. Achieving comparable field intensities with techniques that use radiating antennas requires high power antennas and expensive power amplifiers. Thus, the relative cost of the parallel-plate technique is low. Also, the test structure is relatively simple to construct, operate, and maintain.

There are several disadvantages of the parallel-plate technique, however. First, the plate separation distance limits the size of the EUT. Equipment with dimensions approaching the plate separation distance will substantially perturb the field and produce an impedance mismatch in the TEM line. When large perturbations exist in the line, the field is no longer uniform, the field intensity is no longer accurately defined by $E = V/h$, and impedance mismatches exist which can result in multimoding at higher frequencies. Another disadvantage is that the parallel-plate structure is not a shielded enclosure. Thus, the EUT is exposed to the ambient electromagnetic environment and the structure radiates electromagnetic energy.

The second type of TEM transmission line test structure is the tri-plate line. This structure is a balanced parallel-plate line which consists of a ground plate (or plane) on each side of a center plate (or conductor). In general, the performance characteristics and the advantages and disadvantages of the tri-plate line are the same as the conventional parallel-plate line.

The third type of TEM transmission line structure is the TEM cell. Because the TEM cell is a closed structure, the interaction between the test volume and the surrounding electromagnetic environment is minimized. The TEM cell consists of a tri-plate transmission line with metal side walls between the two ground plates [9]. The center plate is inside of a rectangular ground conductor which forms an expanded "rectangular coaxial" transmission line. The ends of this expanded transmission line are tapered as shown in Figure 4 to standard coaxial transmission line dimensions. The factors which affect the dimensions of the TEM cell are interrelated; they include the usable test volume, the upper frequency limit, the field uniformity, and the cell VSWR or mismatch. For example, the dimensions of the cell (b/2, W and L in Figure 4) must be at least three times the maximum dimension of the EUT to minimize field perturbations in the cell. At the same time, to maintain E-field uniformity in the test volume, the upper frequency limit must be below the cell's multimoding frequency, which is inversely proportional to the dimensions of the cell. Thus, to accomodate larger EUT's the cell's dimension must be increased; however, increasing the dimensions of the cell lowers the upper frequency limit of operation.

The optimum geometry for maximum test volume and maximum test frequency has been found empirically to be one in which b equals W [9]. The E-field uniformity in the usable test volume of a cell with this geometry is within + 2 dB. The E-field uniformity can be improved to + 1 dB by reducing b to 0.6 W, i.e., by reducing the usable test volume.

In order to achieve E-field uniformity, the maximum test frequency must be sufficiently low such that the fields in the cell propagate in the TEM mode, i.e., such that multimoding does not occur. Multiple modes can exist in the TEM cell at frequencies above the cutoff frequency of the next higher order propagation mode. The first higher mode is the TE_{10} mode and by waveguide analogy its cutoff frequency is

$$f_{c10} = \frac{c}{2W},$$

where $c = 3 \times 10^8$ meters/second is the velocity of propagation and W is the width of the cell in meters. For an empty TEM cell, or for one in which the EUT is electrically small, it has been reported that the maximum operating frequency can be approximately 50 percent higher than f_{c10} [10] , [11]. Recent investigations have also indicated that the upper operating frequency can be extended even further by appropriately locating RF absorbing material in the cell [11]. The absorbing material effectively dampens the high frequency resonances and thus reduces multimoding in the cell at higher frequencies. This absorber loaded cell appears to improve the measurement accuracy when compared to that of the unloaded cell at frequencies greater than f_{c10}; however, at these higher frequencies, the accuracy still appears to be significantly less than that expected at frequencies below f_{c10}.

A typical test setup utilizing the TEM cell at frequencies above 1 MHz is shown in Figure 5. At frequencies below f_{c10}, the E-field is given by the following equation:

$$E_c = \frac{P_n R_z}{b/2}$$

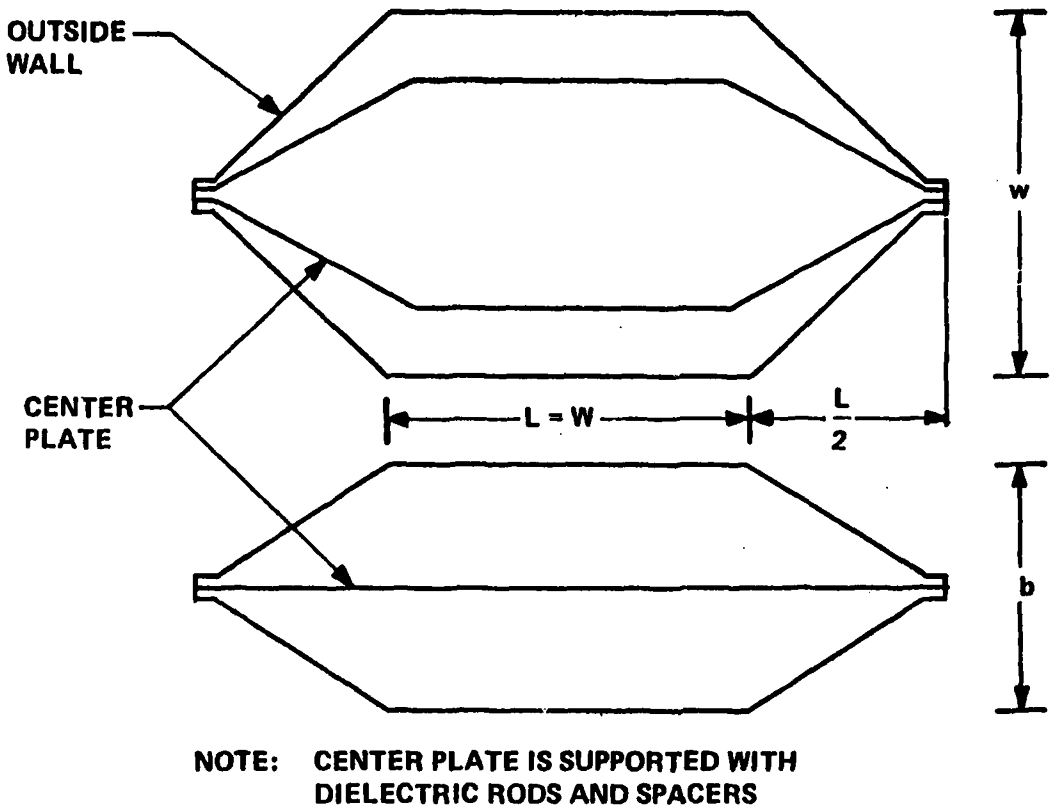

Figure 4. Geometry of TEM Cell.

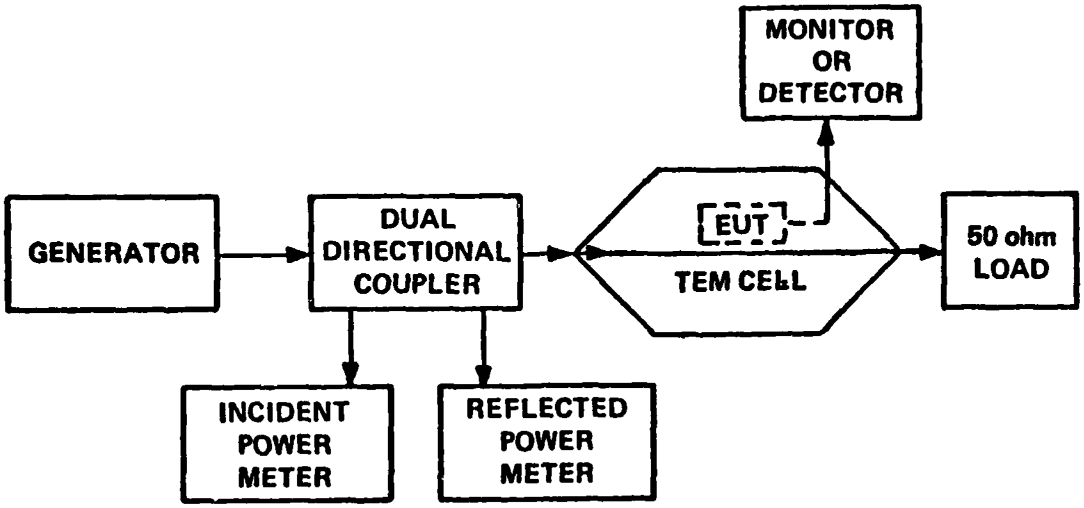

Figure 5. Susceptibility Test Configuration Using TEM Cell From 1 MHz to f_{c10}.

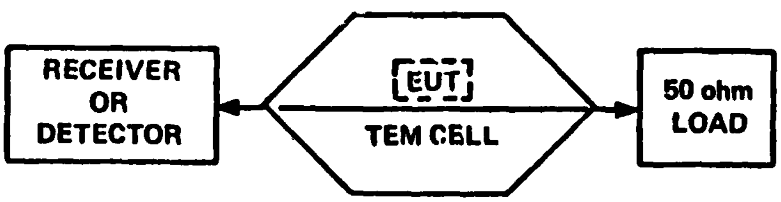

Figure 6. Emission Test Configuration Using TEM Cell.

where

E_c = the magnitude of the E-field,
P_n = the net power flowing through the cell,
R_z = the real part of the cell's characteristic impedance, and
b/2 = the distance between the cell's outer wall and center plate.

The dual directional coupler and power meters are replaced with a voltage monitor tee and an RF voltmeter for frequencies below 1 MHz. Then the E-field is given by the following equation:

$$E_c = \frac{V_c}{b/2}$$

where V_c is the measured voltage at the input of the cell. An error analysis of this susceptibility measurement technique has shown that the uncertainty in the value of E_c is less than $\pm$ 2 dB depending on the EUT's perturbation of the field [9].

The TEM cell has been used as shown in Figure 6 to perform emission measurements based on the assumption of reciprocity [10], [11]. The radiated emissions of the EUT are coupled to the cell's ports via the TEM propagation mode of the cell. The measured RF energy is used to calculate the relative emissions of the EUT based on the receiver characteristics, the coupling properties of the cell, and the loading effect of the EUT.

When an EUT is placed in a TEM cell, its radiation resistance is changed relative to its free-space radiation resistance. Hence, the emissions of an EUT measured in a TEM cell must be corrected to obtain the free-space emissions. The correction procedures have been theoretically and experimentally investigated for electrically small (dimensions much less than a wavelength) emitters [12], [13] [14]. These procedures involve modeling the electrically small emitting device with equivalent electric/magnetic dipoles appropriately excited in amplitude and phase to determine its free-space emission characteristics. The investigations have shown that the resulting uncertainty in the measured E-field emissions are less than 5 dB. Correction procedures for larger EUT's have not been developed and have not been verified for H-fields and composite fields; however, research in these areas is being conducted [13],[14]. A review of the literature has not revealed any data which compares the results of radiated susceptibility and emission test on actual equipments in a TEM cell with the results of the same tests in the open field or in an anechoic chamber. In order to define the accuracy of this test technique, such comparative tests should be performed for various sizes of EUT's.

The TEM cell offers several potential advantages in measuring the susceptibility and emission characteristics of small equipments and devices. It can be used from dc to f_{c10} to provide fields from 10 μV/m to 500 V/m, and the smaller cells are portable and simple to build. The cell's construction cost is lower than conventional anechoic chambers and shielded enclosures and the uncertainty in the E-field for susceptibility testing is only a few dB.

Because of its TEM mode of operation, the cell has a linear phase response from dc to near f_{c10} and can thus be used for swept frequency measurements.

The major limitations of the TEM are: (1) the inverse proportionality between its size and the upper frequency limit; (2) the restriction on the EUT size imposed by cell dimensions; (3) the inaccuracy of the emission measurements on devices that are not electrically small; and (4) the apparent lack of comparative data with open-field and anechoic chamber tests on actual EUT's of various sizes.

The final type of TEM transmission line test structure is the long-wire antenna. This method involves a wire suspended on insulators between opposite walls of a conventional shielded enclosure as shown in Figure 7. The long-wire antenna method is generally used for making susceptibility measurements at frequencies below 30 MHz. The wire is installed along the longest dimension of the enclosure and at a distance from the ceiling between one-fourth and one-third the interior height of the enclosure [15]. At low frequencies, the enclosure operates in a TEM mode with the wall as the outer conductor. Therefore, the termination resistances are chosen to match the characteristic impedances of the concentric feed-line and the antenna, respectively [15], [16]. The EUT is located on a ground plane in the center of the enclosure and directly under the center of the long-wire antenna. The field intensity (E_d) at the EUT location is given in microvolts per meter by the following equations:

$$E_d = \frac{1}{K_d} E_1$$

and

$$\frac{1}{K_d} = \frac{2.36 \times 10^3}{Z_1} \left[\frac{1}{d} + \frac{1}{2d_1 - d} - \frac{1}{2d_2 + d} \right]$$

where

E_1 = voltage in μV to the input of the concentric line,
K_d = attenuation factor,
Z_1 = characteristics impedance of the line, and
d, d_1, and d_2 = distances in meters as shown in Figure 7.

The long-wire antenna test chamber can accommodate relatively large EUTs. It provides isolation from the ambient electromagnetic environment and can develop relatively high field intensities. Also, the long-wire antenna is simple and can be installed in a shielded enclosure in a short period of time. The major limitation of the long-wire antenna test configuration is the upper frequency limit of approximately 30 MHz.

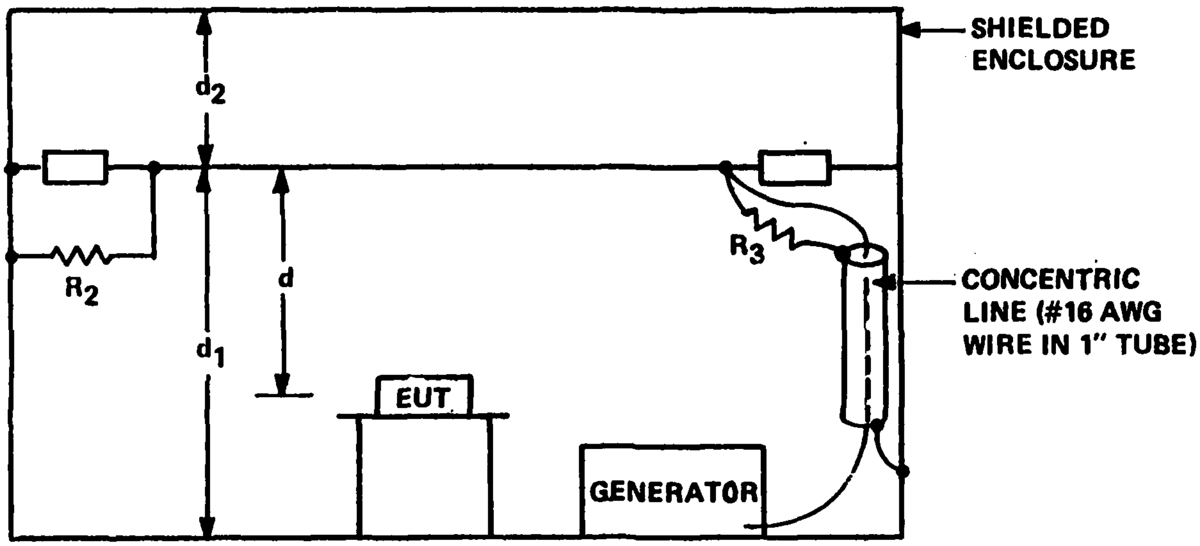

Figure 7. Long-Wire Antenna Test Chamber.

3.8 Statistical Sampling

A major shortcoming of current deterministic measurement methods is that the measured radiated emission and susceptibility characteristics of a system cannot readily be extrapolated from the specific measurement configuration employed to other system configurations*. Thus, the use of the measurement results in predicting the EMC/EMI performance of a system when tactically deployed is limited. In view of the multiplicity of configurations likely to occur in practical system installations, the need for a measurement method which will circumvent this shortcoming is obvious. One such method that offers promise is the statistical sampling approach [17],[22]. The approach involves a statistical description of case emission and susceptibility, the concept of which is illustrated in Figure 8. Figure 8(a) shows the plot of a probability distribution function E(p) describing the radiated field strength at a given frequency and at a fixed distance from a particular culprit case. The function defines the probability that the field strength at a distance R_o from the center of the case would be less than any given level if the case were randomly oriented in three-space. Figure 8(b) illustrates a corresponding probability distribution function S(p) describing the susceptibility of a particular victim case for a radiated field of the same frequency. Here, the function defines the probability that the victim case will fail in a field the strength of which is less than a given level if the case is randomly oriented in three-space.

The probability of mutual interference can be predicted from the data of Figure 8. The probability density functions may be obtained from their associated probability distribution functions by differentiation. "Joint failure" occurs when the emission level of the culprit case is greater than the susceptibility level of the victim case for a particular orientation. The joint probability of failure, P(F), may therefore be obtained by integrating the associated probability density functions with the appropriate limits of integration, resulting in the equation

$$P(f) = 1 - \int_{-\infty}^{\infty} \int_{-\infty}^{P} E'(\omega)\, S'(p)\, d\omega dp$$

where E' and S' are the derivatives of E and S, respectively. This equation can be reduced by performing the first integration, resulting in the expression

$$P(f) = 1- \int_{-\infty}^{\infty} S'(p)\, E(p)\, dp$$

*Deterministic measurements performed in the near-field of a system cannot be readily translated to other distances in the near-field, to the far-field, or to other measurement or deployment configurations. Deterministic measurements performed in the far-field of a system can be translated to other distances in the far-field, but are not useful in assessing near-field problems.

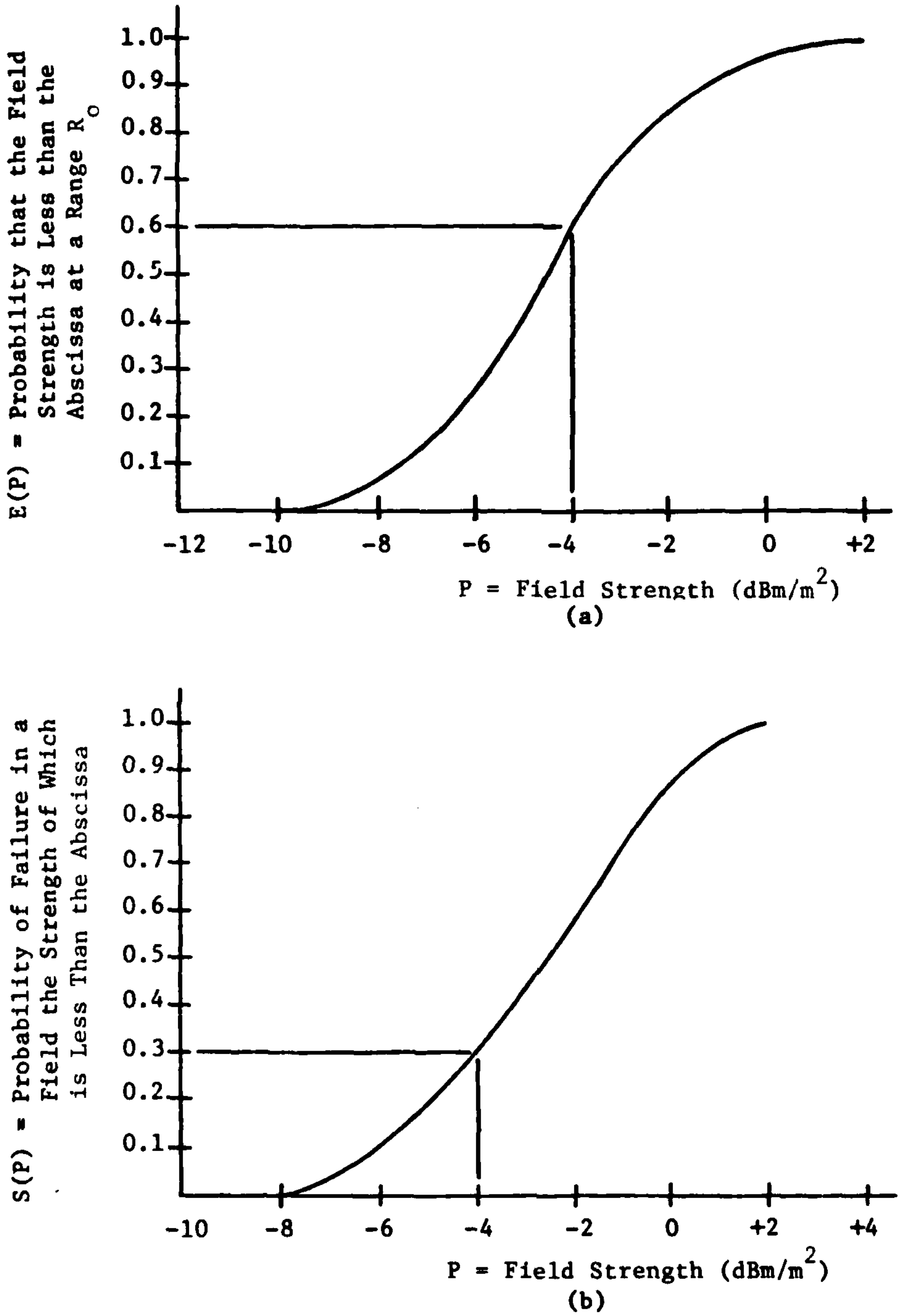

Figure 8. Sample Statistical Descriptions of Case Emissions and Case Susceptibility. [5]

The integral may be readily evaluated using numerical techniques. It should be noted that P(F) can be calculated for separation distances other than R_o by appropriately modifying the field strength levels of Figure 8(a) using the inverse-square-law for radiated fields. It should also be noted that, although the sample calculation assumed only one interference frequency, P(F) can be calculated for any number of possible interfering frequencies [17].

A measurement technique for statistically describing case emissions in the manner indicated in Figure 8 (a) has been evaluated [17] . An experiment was conducted in which measurements were made on simulated culprit sources to determine probability distribution functions for the source emissions. This experiment consisted of statistically describing the three-dimensional radiated fields about each of the sources at different frequencies and under three different environmental conditions: an anechoic chamber, a typical work location in a laboratory, and a shielded enclosure. The shielded enclosure measurements were made using the hooded antenna technique.

Figure 9 compares the probability distribution functions obtained from measurements made in the anechoic chamber, laboratory, and shielded enclosure for one simulated source at one frequency. The distribution functions were expressed in terms of relative power levels for purposes of convenience in illustrating the characteristics of the functions; conversion to absolute levels of field strength or power density can be accomplished through the use of appropriate calibration factors. The data of Figure 9, as well as data recorded on other simulated sources and at other frequencies, show that the power distribution measurement technique can be used to obtain highly repeatable radiated emission measurements in a laboratory and/or a shielded enclosure that routinely are within $\pm$ 1.5 dB of corresponding values measured in a free-space or anechoic chamber environment [17], [22].

Used in conjunction with appropriate statistical descriptions of case susceptibility, case emission data accumulated with the power distribution measurement technique could be used to predict the probability of electromagnetic compatibility (or incompatibility) in actual field equipment setups. The statistical sampling technique offers a number of advantages including a capability for predicting interference problems independent of the separation distance between an emitter and receptor, a large degree of flexibility in the test environment and results which are repeatable and correlatable with free-space results. The major drawbacks primarily concern the complexity of the measurements and the relatively extensive test time and data reduction requirements. Additional investigations are required, particularly with regard to radiated susceptibility measurements, in order to reduce this technique to practice.

3.9 Other Methods

Various methods, other than those previously discussed, which can potentially be used to make radiated emission and/or susceptibility measurements include the low-Q enclosure, the compact range, and the near-field probe.

Low-Q (lossy wall) enclosures are a modified form of the conventional shielded enclosure in which nonmetallic lossy walls of low reflectivity are used to reduce reflections and attenuate wall coupling. Two investigations of

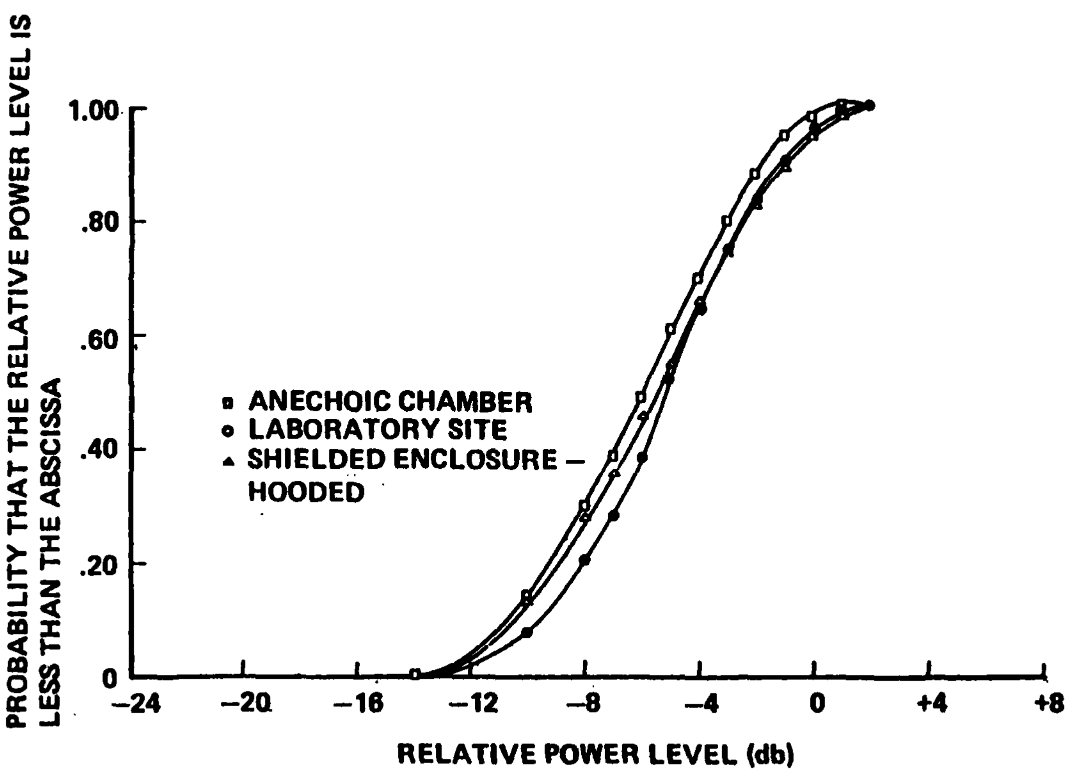

Figure 9. Average Cumulative Distributions For a Simulated Source in Three Environments.

the feasibility of low-Q enclosures have been conducted. The first investigation [23] consisted of coating the inside walls of a conventional shielded enclosure with a lossy material. This material reduced the Q of the enclosure and, thereby, reduced the 40 dB measurement errors in conventional enclosures by more than 20 dB over the 20 to 200 MHz frequency range. The lossy material was a mixture of graphite and spackling compound with a conductivity of 1.0 mho/m. This lossy wall approach, even though promising, has been evaluated only in scaled models of full-sized enclosures.

The second investigation [24] of low-Q enclosures evaluated the use of an underground room or tunnel as a shielded enclosure. The tunnel walls were solid granite with a relative permittivity of 6. It was found that if the tunnel was sufficiently deep, adequate isolation from the ambient electromagnetic environment could be obtained. Also, measurements indicate that the ± 40 dB measurement errors in conventional shielded enclosures can be reduced to less than ± 5 dB in the low-Q tunnel over the 20 to 100 MHz frequency range. The major disadvantage of performing measurements in low-Q tunnels is their limited accessibility.

The compact range involves the use of a large reflector to collimate the beam from a source antenna so as to provide a planar wavefront as shown in Figure 10 [25]. The diverging rays from the point-source feed are collimated by the range reflector, and a plane wave is incident on the EUT. A uniform plane electromagnetic wave can be created at distances independent of the conventional criterion of $2D^2/\lambda$. The incident wave has a phase variation much less than the $\pi/8$ radians guaranteed by the $2D^2/\lambda$ separation criterion. However, the feed-reflector combination introduces a small amplitude taper across the test zone. Typically, the amplitude tapers are less than 2 dB for microwave frequencies and are much better than can be expected at a distance of $2D^2/\lambda$.

The upper frequency limit of the compact range is determined primarily by the roughness of the reflector surface (i.e., by the deviations of the reflector surface from a true parabola). Deviations in the fabricated surface will result in uncollimated rays which results in a nonuniform amplitude distribution at the EUT. Since even small deviations can result in significant variations from a uniform plane wave, the surface tolerance of the reflector becomes more critical as the test frequency is increased. Compact ranges are commercially available for use at frequencies up to 94 GHz.

The lower frequency limit is determined by the diffraction effects from the edges of the reflector. Discontinutities in the normal flow of currents at the edges produce stray radiation which is not in phase with the collimated radiation. One technique for reducing this stray uncollimated energy is to "roll" the edge of the reflector such that the sharp diffraction edge is relocated behind the reflector. This "rolled" edge technique, however, increases the size and weight of the reflector. Therefore, a tradeoff between the radius of curvature and the acceptable nonuniformity of the field must be made. Analyses have indicated that the radius of curvature should be one wavelength or greater at the lowest operating frequency with an arc length of at least 180.

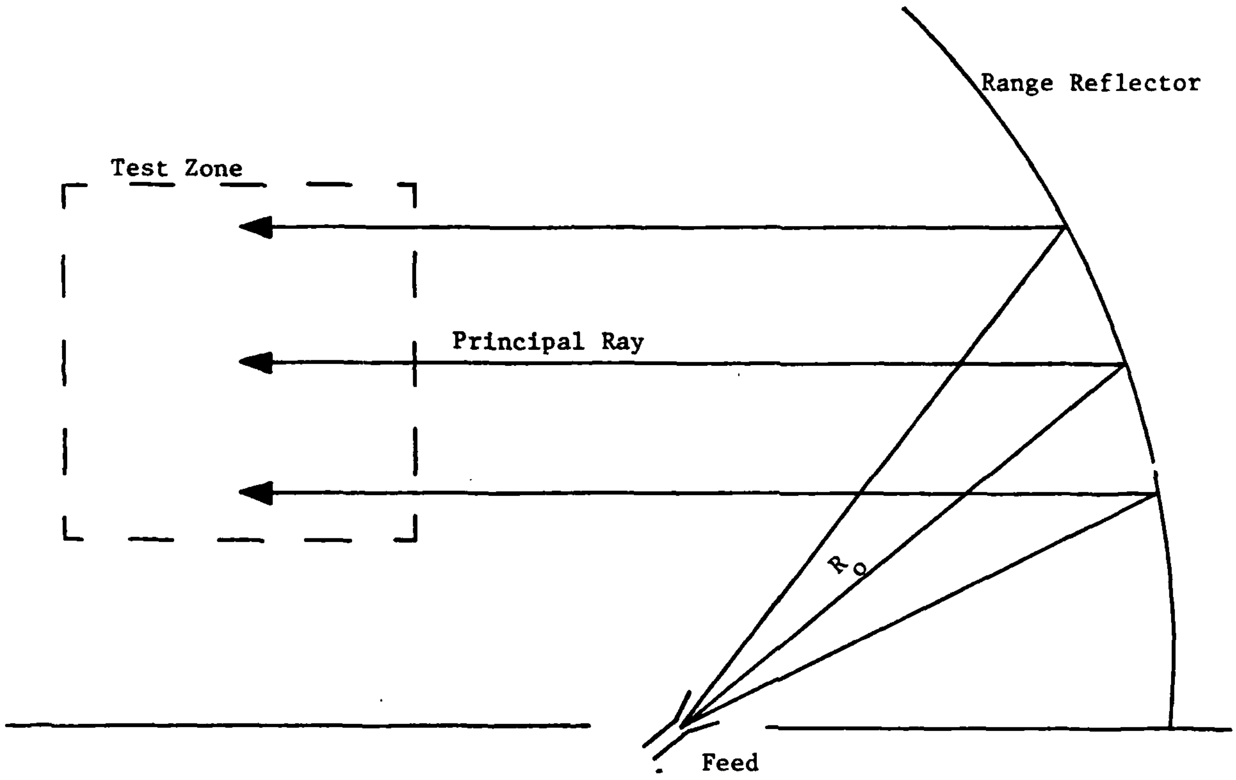

Figure 10. Schematic Representation of Compact Range Employing a Reflector and Feed Horn to Generate a Planar Wave Front. (Rays drawn show concept of equal path distances for all rays)

The compact range is conventionally used as a transmitting system for antenna pattern measurements, gain comparisons, boresight measurements, radar reflectivity measurements, and biological specimen illumination. Hence, the compact range offers promise as a radiated susceptibility measurement technique and it's application to such measurements should be simple and straightforward.

Also, the compact range can potentially be used to perform radiated emission tests. From a simple mathematical description of the coupling between the compact range and the EUT, it has been shown that the transmission equation that results from viewing the compact range as the transmitter is identical to the transmission equation that results from viewing the EUT as the transmitter [26]. This derivation makes use of the concept of a plane wave spectrum, taking the point of view that the compact range acts as an "angle filter" for the plane waves emitted by the EUT.

Although the compact range appears to be applicable for both emission and susceptibility measurements, no information has been found which indicates that the compact range has been employed in performing emission measurements. Thus, an experimental verification of the applicability of the compact range to performing radiated measurements of various EUT's is considered necessary prior to its recommendation as an alternate measurement technique for MIL-STD-462 type tests.

The compact range technique requires a reflector and feed. Otherwise, the instrumentation is similar to that required for open-field or anechoic chamber tests. The chief advantage of the compact range is that it occupies a relatively small space which allows it to be located indoors. The chief limitations are that the reflector must be larger than the EUT and that the reflector must be constructed very precisely.

The near-field measurement technique has been used primarily to measure the radiation characteristics of antennas [26], [27], [28]. With this technique a computer-controlled probe antenna is used to measure the amplitude and phase of two orthogonal components of the near field of the antenna-under-test. These data, in conjunction with the probe positional data, are then transformed to far-field data using a modal expansion technique. Basically, this technique consists of calculating the far fields from a plane wave, or wavenumber spectrum, representation [29] of the measured near fields. It is based on a well-known result of the theory of electromagnetic wave propagation in a linear isotropic medium. In particular, if the amplitude and phase of the tangential component of the electric field are well known over any surface enclosing a radiating structure, the electric field at any point in space external to the surface can be calculated. Far field data are calculated through the use of a plane wave spectrum representation of the integral of the electric fields radiated by the differential elements of the bounding surface. The effects of the measurement probe are removed via an inverse spatial filtering procedure [28], [30].

The near-field measurement technique appears to be appropriate for determining the far-field radiated emission characteristics of EUTs; however, an equivalent approach for performing susceptibility measurements is not known. Furthermore, the limitations of the near-field technique should be experimentally determined for actual EUTs in terms of the size and types of EUTs, the applicable frequency range, and other related parameters.

Since the measurements are computer controlled, the near-field measurement technique is semi-automated and can probably be easily fully automated. The major limitations are: (1) the test time tends to be high because of the large number of sample points that must be measured in the near field and because of the data processing required to transform the measured data to far-field data, (2) the large cost associated with the near-field measurement system, and (3) the restriction to radiated emissions test only.

4.0 COMPARATIVE EVALUATION OF MEASUREMENT TECHNIQUES

4.1 Introduction

A common set of parameters was selected as the criterion to be used in evaluating and characterizing the various measurement techniques. A total of fifteen parameters were defined as being most significant and meaningful for this evaluation. Where possible, a quantitative comparison of these parameters is used to illustrate the applicability of the various measurement techniques. The values of seven of the defined parameters can be quantified and are presented in Table I for each measurement technique. The remaining eight parameters do not lend themselves to quantification and hence were rated on a relative basis. The values for the quantified parameters were obtained from an extensive search of the literature and from catalogues on commercially available test facilities. Engineering judgement was used in those instances where specific values for the quantified parameters could not be found and also for the subjective ratings of those parameters which could not be quantified.

4.2 Comparison of Techniques

The first parameter with quantitative values in Table I is the magnitude of the typical errors encountered when using each measurement technique. In general, this parameter is the expected error relative to free-space measurements; it includes the typical variations in emission and susceptibility results due to reflections, repeatability, changes in test sites and operators, etc. Obviously, the noted errors are applicable only to the frequency range over which the measurement technique is valid. Since the shielded enclosure technique typically exhibits errors of ±40 dB at frequencies above the first resonant frequency of the enclosure, it must be specifically noted that the error in Table I for this technique applies only to measurements at frequencies which are significantly below the first resonant frequency.

The majority of the measurement techniques in Table I yield typical errors of only a few dB. These errors are graphically presented in Figure 11 to aid in comparing the various techniques. In terms of errors relative to free-space emission and susceptibility measurements of actual EUTs, the anechoic chamber (± 2 dB) is best. The errors obtained with the shielded enclosure (at low frequencies), the hooded antenna, the near-field range, and the compact range are only slightly greater at ±3 dB. Because of the possibility of ground reflection errors which are site dependent, the errors for the open field are estimated to be ± 4 dB. The errors for the two mode perturbation techniques are estimated to be ± 6 dB. The low Q enclosure technique typically exhibits errors on the order of ± 20 dB.

The values of the errors for the three TEM transmission line techniques are based on the calibration of the electric field in the empty test chamber prior to performing susceptibility tests. That is, without an EUT, the uniformity of the electric field can be maintained within ± 2 dB over the test volume. However, accuracy data based on comparative tests relative to other measurement techniques was not located. Also, the typical errors associated with the statistical sampling technique (± 1.5 dB) are based on comparisons of the results obtained when this technique is used in different test locations.

TABLE I. QUANTITATIVE COMPARISON OF MEASUREMENT TECHNIQUES

Technique	Typ. Errors Encountered	Maximum Dimension Of EUT	Maximum Frequency Range	Isolation of Test Environment	Sensitivity	Field Intensity Limit	Typ. Cost (5)
Open Field	± 4 dB	Unlimited	Unlimited may require FCC Approval	0 dB	30 μV/m	> 100V/m	> $100,000
Shielded Enclosure	± 3 dB (1)	10 ft.	200 KHz to 20 MHz	> 100 dB	30 μV/m	> 100 V/m	$1,000 to $100,000
Anechoic Chamber	± 2 dB	10 ft.	50 MHz to >40 GHz	> 100 dB	10 μV/m	> 100 V/m	$10,000 to $100,000
Hooded Antennas/ Part. Anec. Cham.	± 3 dB	10 ft.	200 MHz to >12 GHz	> 100 dB	30 μV/m	> 100 V/m	$1,000 to $10,000
Mode-Stirred Enclosure	± 6 dB	10 ft.	100 MHz to >18 GHz	> 100 dB	10 μV/m	> 100 V/m	$10,000 to $100,000
Mode-tuned Enclosure	± 6 dB	10 ft.	100 MHz to >18 GHz	> 100 dB	< 10 μV/m	> 500 V/m	$10,000 to $100,000
Parallel Plates	± 2 dB (2)	1/2 ft.	DC to 30 MHz	0 dB	< 10 μV/m	< 500 V/m	$100 to $1,000
TEM Cell	± 2 dB (2)	1/2 ft.	DC to 1 GHz (4)	> 100 dB	< 10 μV/m	< 500 V/m	$1,000 to $10,000
Long Wire Antenna	± 2 dB (2)	2 ft.	DC to 30 MHz	> 100 dB	30 μV/m	> 100 V/m	$1,000 to $10,000
Statistical Sampling	± 1.5 (3)	Test Site Dependent	Requires Further Investigation	Test Site Dependent	30 μV/m	> 100 V/m	$1,000 to $10,000
Low Q Enclosure	± 20 dB	10 ft.	20 MHz to 200 MHZ	> 100 dB	10 μV/m	> 100 V/m	$10,000 to $100,000
Compact Range	± 3 dB	5 ft.	400 MHz to 94 GHz	0 dB	30 μV/m	> 100 V/m	$10,000 to $100,000
Near-Field Range	± 3 dB	3 ft.	100 MHz to 18 GHz	0 dB	10 μV/m	N/A	> $100,000

Notes:
1. Invalid technique above 20 MHz.
2. Based on E-field calibration.
3. Based on repeatability in different test locations.
4. Upper frequency depends on size of the cell.
5. Estimates based on 1981 costs.

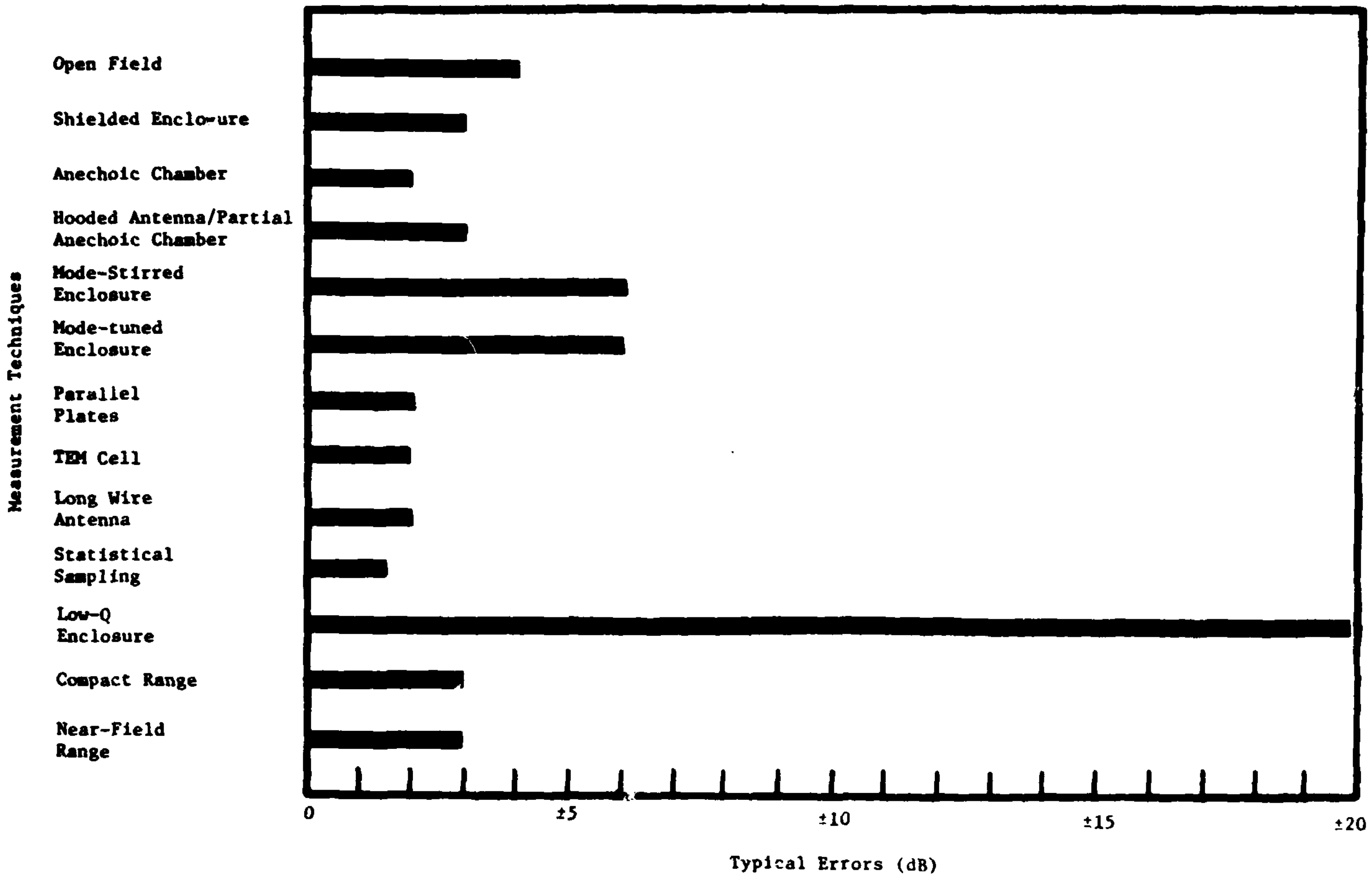

Figure 11. Range of Errors Typically Encountered for Various Measurement Techniques.

Further investigations are required to determine the errors obtained when performing emission and susceptibility measurements with this technique relative to the other techniques.

These values for the typical measurement errors can easily vary 1 to 2 dB. In a technology where 2 to 3 dB is considered small, the errors obtained with several of the techniques is small and, although some of the errors should be improved, the only one which is considered excessively large is for the low Q enclosure.

The "maximum dimension of EUT" parameter in Table I is the maximum value of the largest of the three dimensions of the EUT. If the three dimensions are the same, i.e., a cube, this parameter is then the maximum length of any side of the EUT. This parameter is defined as the largest of the three dimensions of the EUT since complete emission and susceptibility measurements typically require that the EUT be successively oriented in all three spatial directions. If only one orientation is required for the test, it may be possible, depending on the size of the test chamber, for two dimensions of the EUT to exceed the values given in Table I.

For the majority of the measurement techniques, the maximum dimension of the EUT is determined by the size of the test chamber. In general, the measurement techniques which utilize a shielded enclosure as the outer surface of the test chamber can accomodate EUTs with a maximum dimension of approximately 10 feet. The long wire antenna, the compact range and the near-field range techniques can be used with EUTs of two to five feet. The maximum dimension of the EUT when using the parallel plate or TEM cell is small (approximately one half foot or less) because of the smaller dimensions of the test chamber. For comparison, the maximum dimensions of the EUT for the various measurement techniques are graphically illustrated in Figure 12.

In Table I, the maximum frequency range parameter is the frequency range for which test facilities are available and for which the indicated measurement errors can be expected. Again, it should be pointed out that even though the shielded enclosure is currently employed at higher than the listed upper frequency, the errors obtained at these higher frequencies can be as large as $\pm$ 40 dB. The frequency range of the anechoic chamber is determined by the properties of available absorbing material. The only restriction on the test frequency in the open field is that imposed by FCC requirements. The specific frequency limits given for the hooded antenna and the mode perturbation techniques are based on experimental research results; it is expected that the upper frequency limit for these techniques can be extended. The upper frequency limits of the parallel plate and the long wire antenna techniques are given as 30 MHz, since this is the maximum frequency for which these techniques are commonly employed. The upper frequency limit of the TEM cell is 1 GHz for commercially available cells; however, it should be recognized that the dimensions of the cell that operates up to this frequency is only 18 x 18 x 5 inches which severely limits the maximum dimension of the EUT.

The frequency range parameter is graphically illustrated in Figure 13. As this figure shows, only certain techniques cover the same frequency ranges. With the exception of the open-field technique, there appears to be a group of measurement techniques that can be employed at the higher test frequencies and

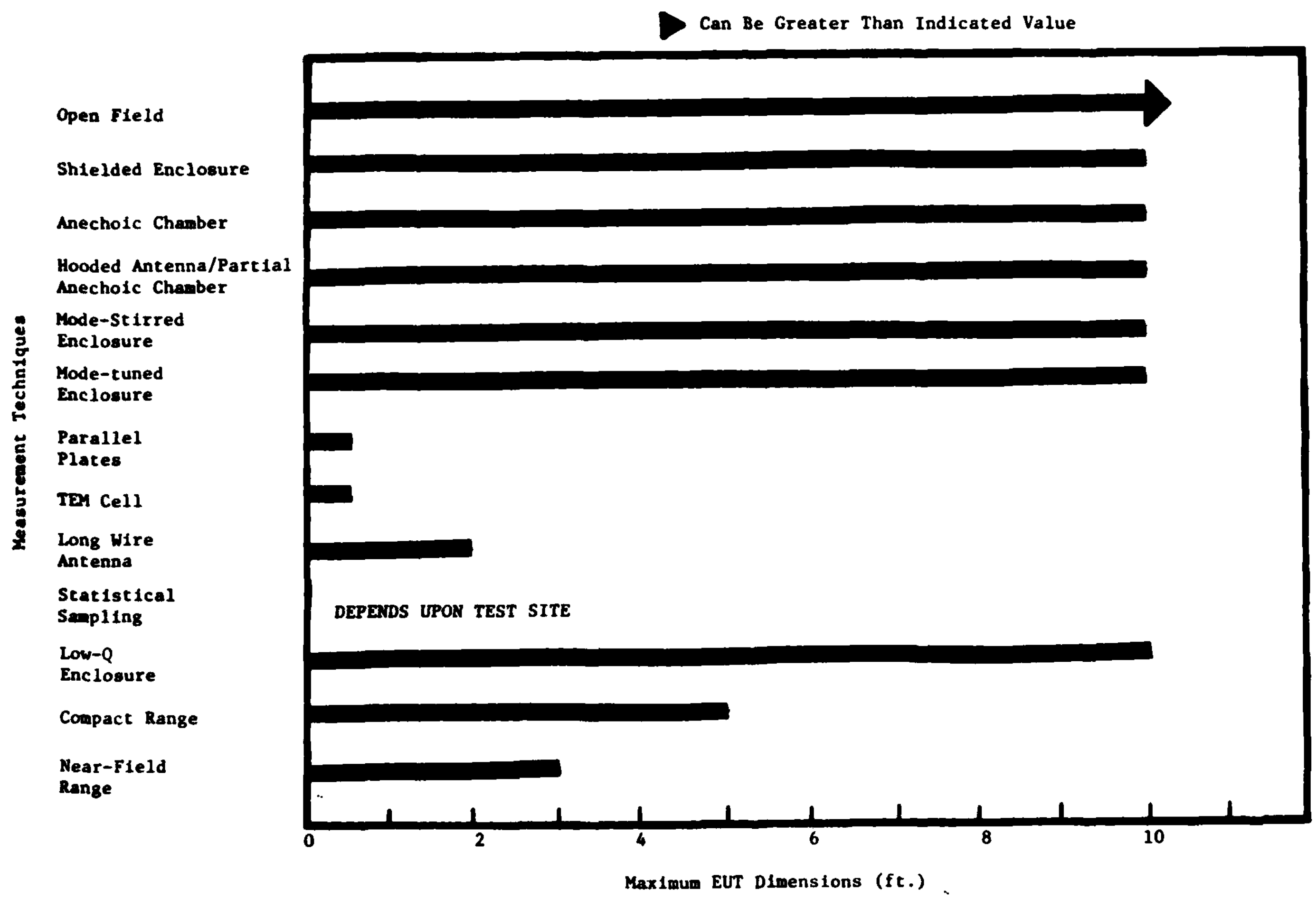

Figure 12. Maximum Dimension of the EUT for Various Measurement Techniques.

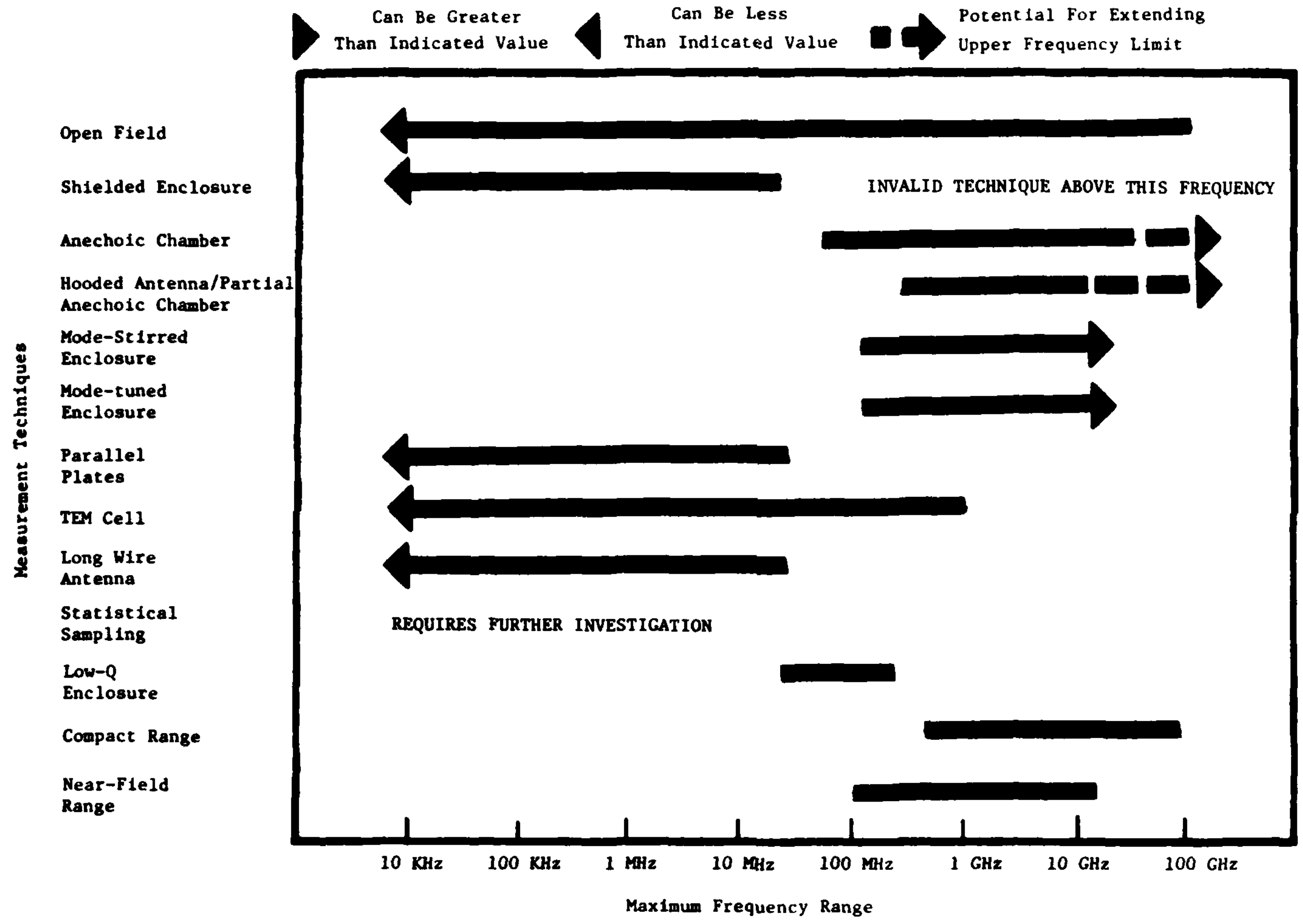

Figure 13. Comparison of Maximum Frequency Range for Various Measurement Techniques.

another group that can be used at the lower frequencies. It is important to note, however, that there is very little overlap in the frequency ranges between these two groups.

As shown in Table I, the isolation provided by the various measurement techniques is either nonexistent (0 dB) or is extremely high (>100 dB), depending on whether the technique involves measurements inside a metallic (shielded) enclosure. The statistical sampling technique may be used where little isolation exists or in a shielded enclosure or anechoic chamber, in which case a high degree of isolation would be obtained. The parallel plate structure may offer some degree of isolation, but the amount (if any) is strongly dependent on the relative orientation of the plates with respect to the emitter/receptor in question. Therefore, if a particular measurement to be performed requires a high degree of isolation, it will be necessary to select a technique which utilizes a metal enclosure.

The maximum sensitivity is defined as the lowest field intensity (in μV/m) which can be detected while performing a radiated emissions test. Figure 14 is a comparison of the maximum sensitivity levels for each of the various techniques. Three techniques are more sensitive (estimated to be 3 μV/m) than the other techniques. The mode-tuned enclosure technique involves maximization of the coupling between the EUT and the receive antenna and should offer a high degree of sensitivity. The parallel plate and TEM cell techniques should also provide for measurement of very low level radiated fields due to the relatively small conductor spacing typically used in these TEM transmission line techniques. The near-field range and the mode-stirred enclosure techniques are also quite sensitive (~ 10 μV/m). The near-field range utilizes a probe in the immediate vicinity of the EUT while the mode-stirred enclosure involves a high degree of coupling between the antenna and the EUT. All other techniques have comparable sensitivites. The estimated sensitivity level of 30 μV/m for these techniques was based on MIL-STD-462 test conditions and the use of commonly available test equipment. It is assumed that the receive antenna in the open field range must be located relatively close to the EUT in order to detect low level emissions.

A comparison of the various techniques in terms of field intensity limit is shown in Figure 15. This limit is defined as the maximum electric field amplitude (in V/m) which may be obtained using typically available equipment. For the mode-tuned enclosure, field intensities of approximately 500 V/m at particular standing wave maxima inside the enclosure can be obtained. Comparable field intensity levels may also be generated in TEM cells and parallel plates, especially for small spacing between conductors (due to the inverse relationship between field intensity and conductor spacing). The near field range may not be used for susceptibility measurements and therefore is not applicable here. All other techniques are estimated to be comparable with respect to field intensity limits.

The limits shown in Figure 15 are intended only to indicate the relative ease with which a radiated field may be established using a particular technique. It is obvious that for any given technique field levels which exceed those shown in the figure can be obtained. For example, field intensity levels exceeding many hundreds of volts/meters can readily be obtained in an anechoic chamber or open-field measurement configuration.

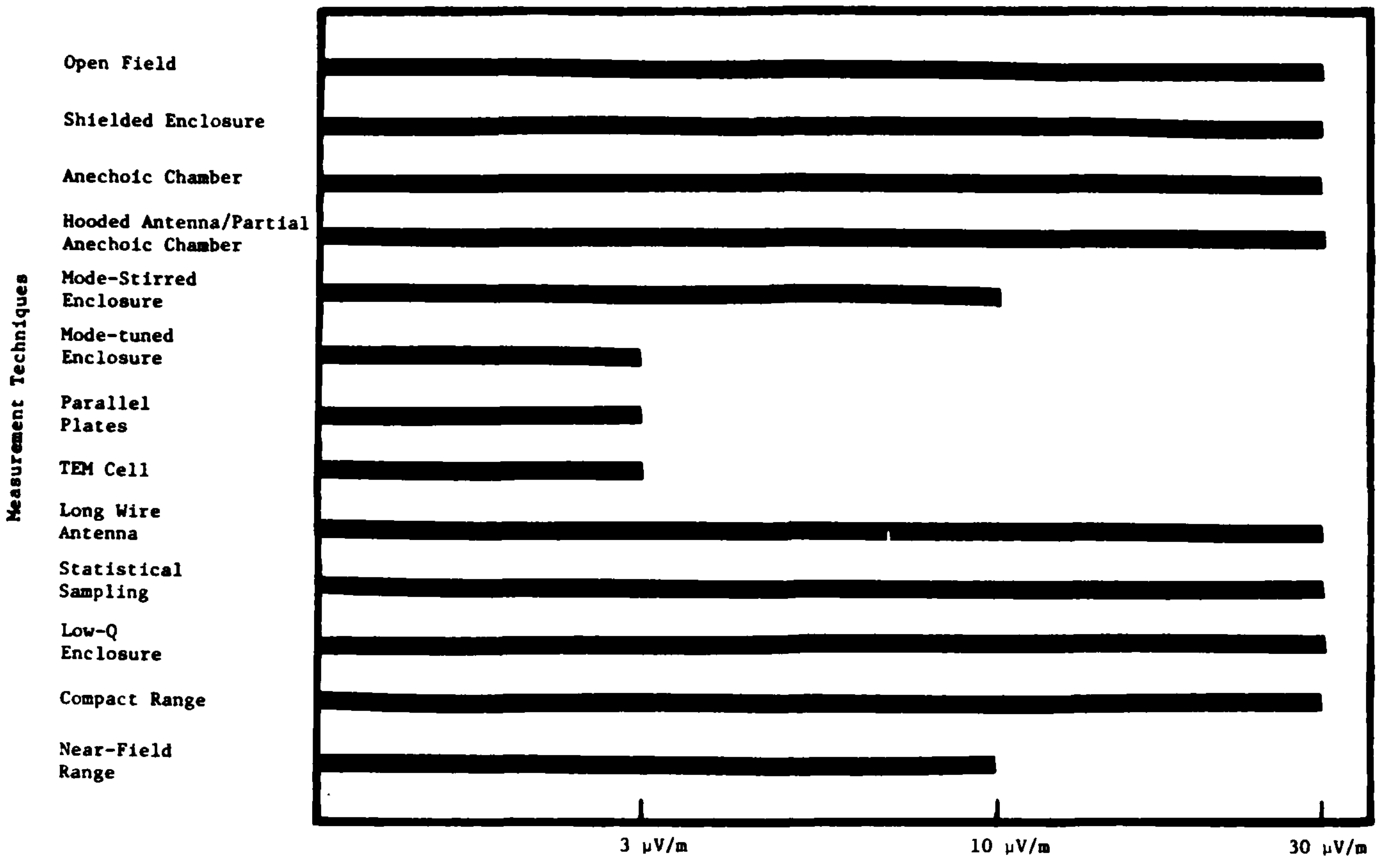

Figure 14. Comparison of Maximum Sensitivity Levels for Various Measurement Techniques.

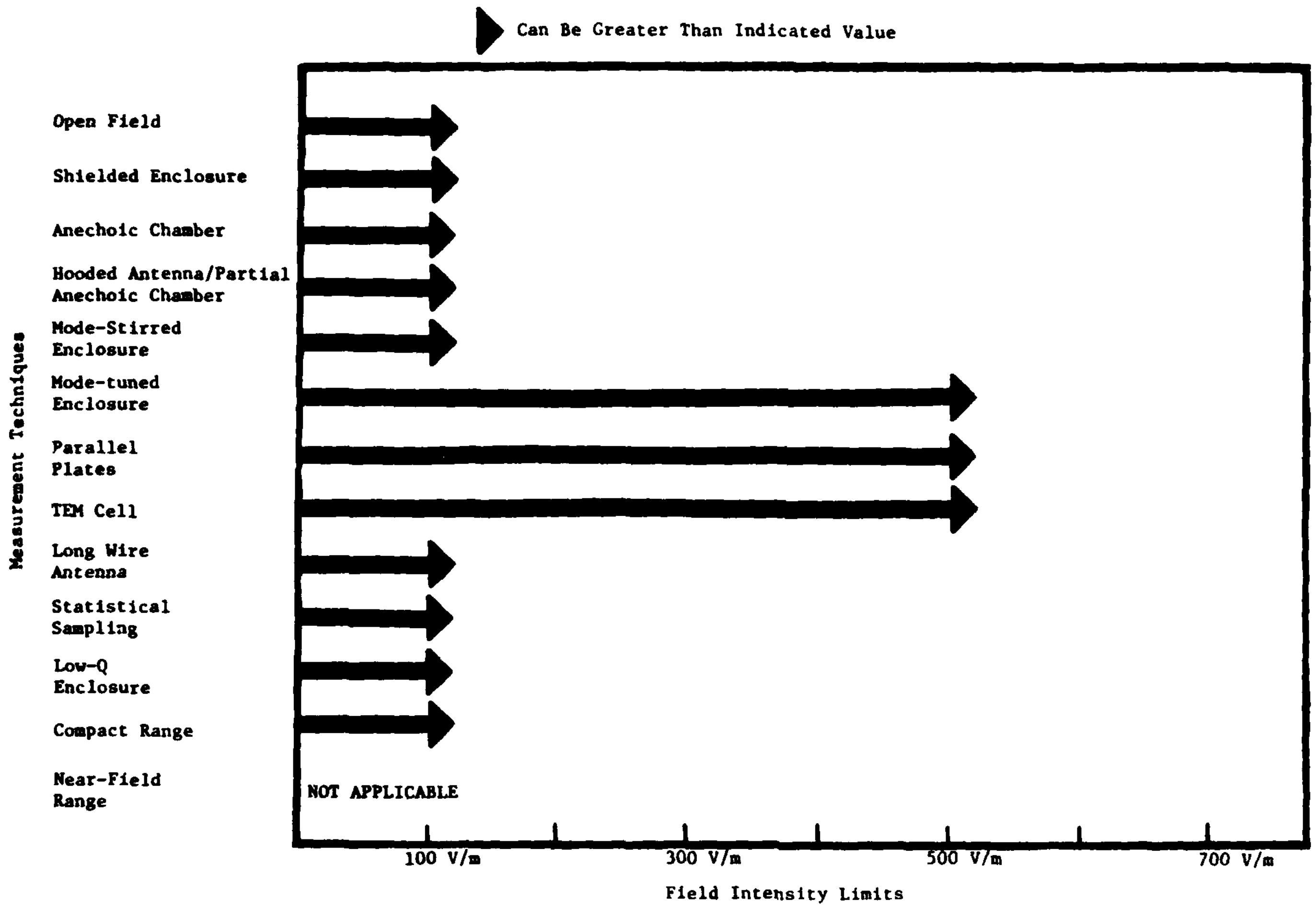

Figure 15. Comparison of Field Intensity Limits for Various Measurement Techniques.

As can be seen from Figure 16, the costs of procuring the facility for a particular measurement technique vary over a considerable range. The cost of a facility may be as low as hundreds of dollars in the case of the parallel plate technique, or well over one hundred thousand dollars for a far-field range. Costs also vary for a given measurement technique, depending upon the particular specifications of the facility. For example, the cost of a moderately sized anechoic chamber (e.g., 12' x 12' x 18') designed for a lower frequency limit of 200 MHz would cost less than one hundred thousand dollars. On the other hand, it would likely cost more than one million dollars to obtain a large chamber (e.g., 32' x 40' x 48') with a lower frequency limit near 50 MHz.

Table II provides a qualitative comparison of the various measurement techniques in terms of the remaining 9 parameters. As indicated previously, these parameters are subjective in nature and have therefore been rated on a relative basis from 1 to 5. A rating of 5 indicates that the technique is excellent with respect to a particular parameter whereas a rating of 1 indicates poor performance with respect to that parameter. It should be noted that the selection and use of a specific technique for a particular application may depend upon parameters not listed in this or the preceding table. For example, the availability of a particular technique (facility, instrumentation, etc.) may be the determining factor in a given instance. The incidental factors and parameters must be weighed in along with those listed in order to make a rational selection of the best technique for a given situation.

The first parameter on which comparative ratings are made is the calibration requirements of a particular technique. The TEM cell and parallel plate techniques are significantly easier to calibrate than are the other measurement techniques*. The field intensity is simply the voltage difference between the plates divided by the plate separation, and this may be calibrated and monitored with relative ease. The long wire antenna is also relatively simple to calibrate, but has the additional requirement of obtaining proper termination of the line. The low-Q enclosure is very difficult to calibrate due to the effects of reflections inside the enclosure.

The statistical sampling technique and the near-field range involve azimuth over elevation and automatic probe positioners, respectively, and have slightly more involved calibration and set-up procedures. All other techniques were rated as average in this category.

The TEM cell and parallel plate techniques are also the least complex in that the setup, calibration, and measurement procedures are quite straightforward, allowing for a minimal amount of training required for the operator. The long wire antenna technique is slightly more complex in that

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* It should be noted that the ratings on the parallel plate, TEM cell, long wire antenna, and compact range apply to radiated susceptibility measurements only, since these techniques have not been verified for use in emissions testing. The shielded enclosure is not recommended above the HF band and therefore has been rated only at frequencies below approximately 20 MHz. Similarly, the near-field range can not be used for susceptibility measurements and has been rated for emission measurements only.

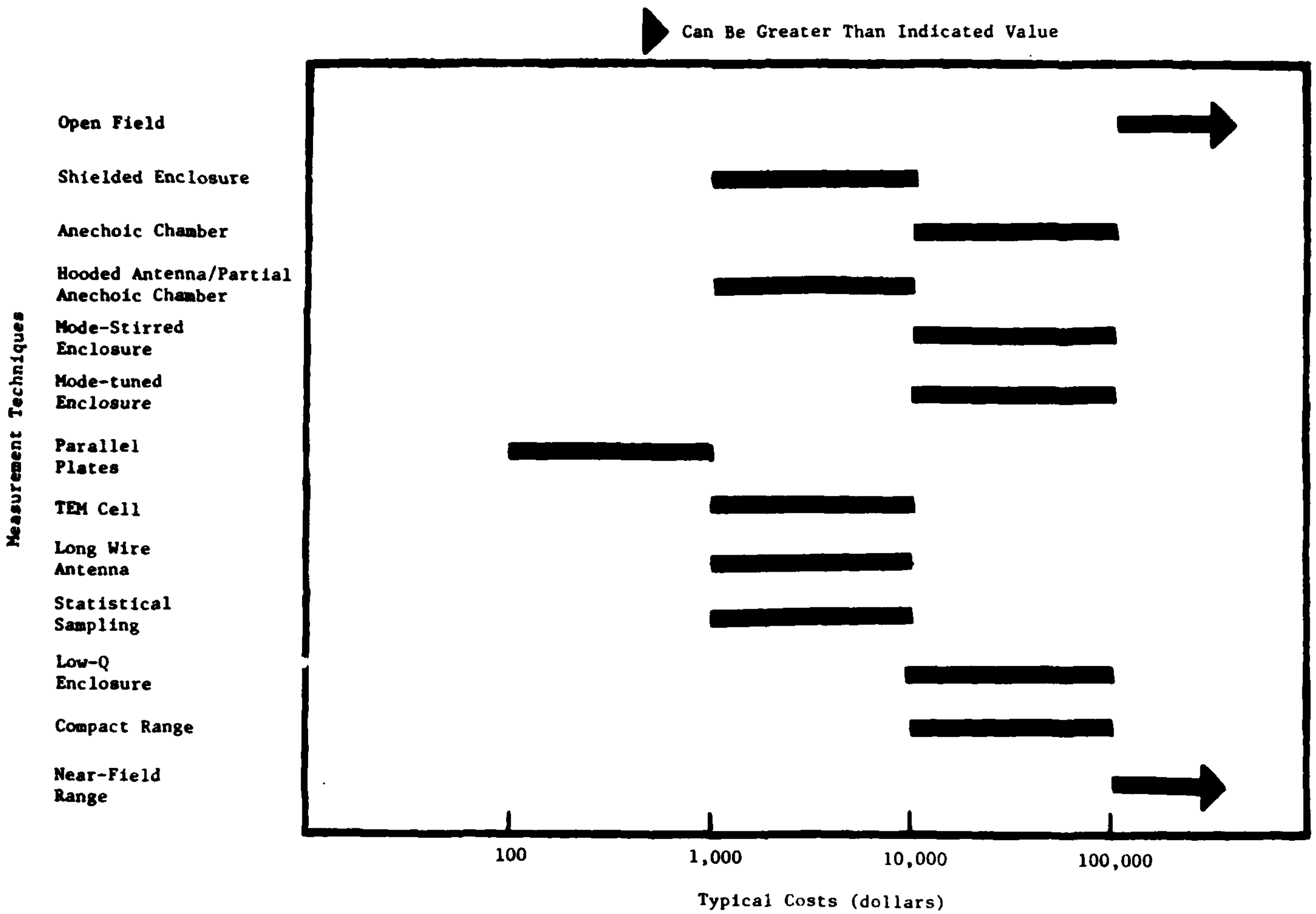

Figure 16. Comparison of Typical Costs for Various Measurement Techniques.

TABLE II. QUALITATIVE COMPARISON OF MEASUREMENT TECHNIQUES (2)

	Calibration Rqmts.	Complexity	Concurrence @ Theory	Data Reduction Rqmts.	Operator Skill Rqmts.	Polarizations Available	Proximity Effects	Time Rqmts.
Open Field	3	4	4	5	3	5	3	2
Shielded Enclosure (2)	3	4	4	5	4	5	4	3
Anechoic Chamber	3	4	5	5	4	5	3	3
Hooded Antenna & Partial Anechoic Chamber	3	3	4	5	3	5	4	3
Mode-Stirred Enclosure	3	2	3	4	4	1	5	4
Mode-tuned Enclosure	3	2	3	4	3	1	5	4
Parallel Plates (3)	5	5	5 (5)	5	5	3	4	5
TEM Cell (3)	5	5	5 (5)	5	5	3	5	5
Long Wire Antenna (3)	4	4	4	5	4	3	4	4
Statistical Sampling	2	1	4	1	2	5	5	1
Low-Q Enclosure	1	4	2	5	3	5	2	2
Compact Range (3)	3	3	4	5	3	5	3	2
Near-Field Range (4)	2	1	4	1	1	5	3	1

Notes:
1. Ratings range from 5 (excellent) to 1 (poor).
2. Ratings Apply to Measurements Made at Frequencies Below 20 MHz.
3. Ratings Apply to Susceptibility Measurements Only.
4. Ratings Apply to Emissions Measurements Only.
5. Based upon E-Field Calibration.

the incident field intensity is now a function of the position of the EUT due to the non-uniform spacing of the conductors in this transmission line. Approximately the same degree of complexity exists for measurements made in an open field, shielded enclosure, anechoic chamber, or low-Q enclosure as for the long-wire antenna technique. The adjustments required in the setup of the hooded antenna/partial anechoic chamber technique and the compact range adds another degree of complexity over the above-mentioned techniques. The hooded antenna/partial anechoic chamber requires adjustment of the antenna to ensure proper coverage of the EUT while simultaneously preventing reflections from degrading the measurement accuracy. The compact range requires focusing the transmitting antenna to ensure a planar wavefront at the EUT. The mode-tuned and mode-stirred techniques are relatively complex due to the requirement in the mode-tune case for adjustments in the antenna matching networks (double-stub tuners, typically) and the additional theoretical complexity involved. The statistical sampling technique requires the use of an azimuth over elevation positioner as well as significant data processing. The near-field range involves complexity in the measurement setup and calibration, and additional complexity in the data processing and probe positioner software.

Concurrence with theory refers to the extent to which the measurement technique conforms to analytical predictions of performance. Concurrence with theory is extremely high in the anechoic chamber technique for both emission and susceptibility measurements. Based only upon the electric field calibration for susceptibility measurements, both the TEM cell and parallel plate techniques are also rated excellent since quite precise planar TEM fields may be generated across the test aperture. The long wire antenna technique was given a slightly lower rating than the other transmission line techniques (TEM cell and parallel plate) due to the additional complexity of non-uniform spacing between conductors. The open field is generally very good, though ground reflections may contribute discrepancies. The shielded enclosure is also quite good when operated below approximately 20 MHz. The hooded antenna/partial anechoic chamber technique demonstrates a high degree of concurrence with theory when set up properly, as does the statistical sampling technique. The concurrence with theory of the compact range is generally quite high, though diffraction effects at lower frequencies and reflector surface irregularities at high frequencies may cause slight discrepancies. The theory of the near-field range, albeit complex, has been verified extensively through measurements and correlation is extremely good. The theory behind the mode-tuned and mode-stirred enclosure is also quite complex and several assumptions (which have yet to be verified) are required and somewhat larger discrepancies may be anticipated. The reflections inside a low-Q enclosure are difficult to account for in theory and significant discrepancies between theory and actual practice often occur.

Most of the measurement techniques require no data reduction at all. Consequently, these measurement techniques received the highest possible rating in this category. The mode-tuned and mode-stirred techniques require the processing of enclosure calibration data versus frequency and, if sampling procedures are used (optional), statistical analysis is required on the data concerning power received or transmitted versus reflector angular position. In the statistical sampling technique, a large amount of data must be collected and subsequently reduced to a probability distribution function. The near-field technique involves processing of the near field amplitude and phase data along with the probe characteristic data in order to obtain far-field results.

The next parameter used to evaluate the various measurement techniques concerns the skill required by the operator. The TEM cell and parallel plate technique require the least skill of all techniques considered. These techniques involve relatively simple setup, calibration, and measurement procedures. The long wire antenna requires a more precise positioning of the EUT since the field intensity is a function of position in the enclosure. The shielded enclosure, anechoic chamber, and mode-stirred enclosure techniques require a moderate amount of skill for setup, calibration, and performance of the measurements. Obtaining accurate results on a open-field range often requires the operator to account for the ground reflections. The relative placement of the antenna and the EUT in the hooded antenna/partial anechoic chamber can influence the accuracy of the results, and the operator should be aware of this potential source of error. In the case of the mode-tuned enclosure, the stub tuners and reflector positioner add to the operator skill requirements. Substantial skill is required for the low-Q enclosure technique in order to avoid large measurement inaccuracies due to reflections from the walls of the enclosure. Operation of the compact range requires, among other things, adjustment of the antenna position to minimize the amplitude and phase taper across the test aperture. The statistical sampling technique requires the operation of antenna directivity measurement equipment. Due to the complexity of the near-field technique, a highly-skilled individual is required. Training time would be significant for an individual unfamiliar with automated testing as is required for the near-field technique.

Most of the measurement techniques considered here are capable of generating or receiving any desired wave polarization. However, a few techniques are limited in this respect. Specifically, the TEM cell, parallel plate, and long-wire antenna techniques are limited to a fixed linear polarization due to the properties of TEM mode transmission. The orientation of the polarization with respect to the EUT may be varied only by rotation of the EUT itself. This may put additional limitations on the maximum dimension of the EUT, especially for the TEM cell and parallel plate techniques. In the case of the mode-tuned enclosure and mode-stirred enclosure techniques, polarization is not preserved and therefore polarization dependent data is unobtainable using these techniques.

Proximity effects can lead to measurement inaccuracies due to unpredictable reflections from objects located in the test area. The low-Q enclosure is the most sensitive to proximity effects due to multiple reflections within the enclosure. The open field, anechoic chamber, compact range, and near field range techniques are less sensitive to proximity effects than the low-Q enclosure. However, precautions are necessary to avoid the existence of reflecting objects (located in the test area) from distorting the measurement results. The shielded enclosure, hooded antenna/partial anechoic chamber, parallel plates, and long wire antenna techniques are less sensitive yet to proximity effects. The shielded enclosure and the long-wire antenna techniques should be used only at frequencies below approximately 30 MHz. At these lower frequencies, reflections are not as critical since the differential path lengths generally are insignificant relative to a wavelength. In the hooded antenna/partial anechoic chamber and the parallel plate technique, the fields are confined, which subsequently decreases the liklihood of proximity effects. The mode perturbation, statistical sampling, and TEM cell techniques are virtually unaffected by the proximity of reflecting objects. In the mode-stirred and mode-tuned enclosures, the measurement results should be independent of reflecting objects since the existence of a reflecting object may be thought of simply as an additional reflector or stirrer. Field uniformity and/or maximum field intensity should be unaffected and so these techniques were rated as excellent in this regard. The statistical sampling technique is also relatively free of proximity effects due to the nature of the probability distrbution function. The fact that results are virtually independent of test site (laboratory vs. anechoic chamber vs. open field) add validity to the independence of results on reflecting object positions. The TEM cell technique is insensitive to proximity effects since the fields are confined within the cell and will not be perturbed by outer disturbances.

As can be seen from Table II, the time requirements vary considerably among the various radiated measurement techniques. Measurements made using the TEM cell or parallel plate technique require the least amount of time due to the relatively quick and easy setup/calibration procedures and the straightforward measurement procedure. The long wire antenna technique requires slightly more time due primarily to the additional time involved with obtaining the proper impedances to terminate the wire. The mode perturbation techniques are worst-case measurement techniques so that once the technique has been set up and calibrated, a single measurement would suffice for a worst-case susceptibility or emission test. The shielded enclosure, anechoic chamber, and hooded antenna/partial anechoic chamber all require a moderate amount of time for setup, calibration, and performance of the actual measurements and each of these techniques was given an average rating for this category. The open field, low-Q enclosure, and compact range require more time than average. Trips to and from an open-field site as well as variable weather conditions can add to the test time. Additional time is required in the low-Q enclosure in order to avoid large measurement inaccuracies due to reflections. Focusing the transmitting antenna adds to the setup time of the compact range. The near-field range and the statistical sampling techniques are the most time consuming radiated measurement techniques. The statistical sampling technique requires a large number of sample points. The near-field range technique involves a large number of near-field measurements and the data processing time for conversion to the far-field can be extensive for electrically large EUTs.

4.3 Applicability of Alternate Techniques to MIL-STD-462 Measurements

The primary objective of this section is to characterize each technique in terms of the selected parameters in order to determine the applicability of each technique for use in satisfying the test requirements of MIL-STD-462. The results of comparative evaluations performed during this program indicate that a number of radiated measurement techniques do indeed qualify as alternates to those recommended by this standard. Each of the alternate techniques has particular merits which may be exploited in a given circumstance or application. As a result, the availability of these additional techniques should enable measurement requirements to be satisfied in a more cost effective manner by allowing for selection of the best technique for a particular application.

The open field is certainly an applicable technique which has the capability of accomodating an EUT of any size with an unlimited test frequency range. It has the disadvantage of being very costly and providing no isolation of the test environment. The anechoic chamber is considered to be the best overall measurement technique in that it approximates a "true" open-field site when operated properly and within its frequency range. However, the anechoic chamber is also a relatively expensive technique. The hooded antenna/partial anechoic chamber is another applicable technique which is not overly expensive yet provides a high degree of isolation with good accuracy. The TEM cell and the compact range are considered to be applicable as radiated susceptibility measurement techniques, but have not been adequately verified as being valid radiated emissions test techniques. The TEM cell is the quickest, most straightforward, and least expensive of all the alternate techniques. However, the EUT size limitations may severely limit its range of applications. The near-field range is applicable for radiated emissions measurements only. The accuracy obtained using the near-field range is high, but so are the costs, complexity, and operator skill requirements.

The mode perturbation techniques and the statistical sampling technique offer a great deal of promise as alternate measurement techniques; however, these techniques have not yet been reduced to practice. Potential advantages of the mode perturbation techniques include relatively high field intensity limits and excellent sensitivity. The facility costs are not excessive and these techniques permit a single worst-case measurement to be performed without the need of rotating the EUT or "sniffing" out the direction of maximum radiation. The statistical sampling technique (though it does not conform to the current approach set forth in MIL-STD-462) represents a different, and probably more meaningful, approach to radiated emission and susceptibility measurements. The statistical approach is directed towards assessment of the interference potential of a system in its operating environment. The errors associated with the low-Q enclosure are considered to be excessive and this technique is not considered to be applicable as an alternate technique to MIL-STD-462 measurements.

5.0 VOIDS AND DEFICIENCIES IN CURRENT RADIATED MEASUREMENT METHODOLOGIES

5.1 Introduction

From the results of Sections 2, 3, and 4, a number of deficiencies which exist in current radiated emission and susceptibility measurement methodologies can be identified. These deficiencies are discussed in the following subsections, along with actions which are deemed necessary for their resolution. Section 5.2 identifies specific problem areas which should be addressed to remove deficiencies and improve the capabilities of specific radiated emission and susceptibility measurement techniques. Section 5.3 addresses what is considered a more fundamental problem with current EMC/EMI measurements -- the fact that EMC/EMI measurement philosophies have not kept pace with the overall needs and objectives of the EMC community nor with the state-of-the-art in measurement technology.

5.2 Deficiencies In Current Measurement Techniques

Sections 3 and 4, respectively, provide a description and comparative analysis of the limitations of those measurement techniques which are currently used or have been proposed for use in performing radiated emission and susceptibility measurements. From these descriptions and comparisons, a number of deficiencies can be identified whose resolution would significantly enhance current EMC/EMI measurement capabilities. These deficiencies can generally be divided in three categories: (1) deficiencies which prevent the maximum utilization of measurement techniques which are currently in use, (2) deficiencies in reducing to practice those measurement techniques which have been identified as possible alternates to currently used techniques, and (3) deficiencies related to the lack of correlation and proper utilization of measurement techniques and results. A summary description of deficiencies in these three categories is outlined in the following paragraphs. It is to be noted that none of the identified deficiencies are a result of technology limitations, but rather have resulted from a lack of effort in advancing the state-of-the-art in EMC/EMI measurement methodology.

1. DEFICIENCIES IN MAXIMIZING THE UTILIZATION OF MEASUREMENT TECHNIQUES

Techniques for Radiated Emission Measurements. With the exception of the near-field range, all of the measurement techniques described in Section 2 and 3 can be used or have the potential for use in performing radiated susceptibility measurements. However, the techniques which are currently employed for radiated emissions are limited to the open-field, shielded enclosure, anechoic chamber, and hooded antenna techniques. Efforts should be made to determine the applicability of the other techniques to performing emission measurements and to reduce to practice those techniques which are suitable for this purpose.

Extension of Measurement Parameters. The utilization of many of the identified measurement techniques is limited by a lack of knowledge of the maximum range of application of the technique. For example, the upper frequency limit of many of the techniques has not been established. The need for extending this parameter is perhaps obvious when it is considered that within the next decade, systems which operate at frequencies greater than 100

GHz may become operational. For some of the techniques (i.e., parallel-plate structure, TEM cell), an extension of the upper frequency limit is not possible. However, the anechoic chamber, hooded antenna, compact range, and statistical measurement techniques offer the possibility of measurements at frequencies which are much higher than those employed in current EMC/EMI measurements(as exemplified by MIL-STD-461/462). The upper frequency limit of the mode perturbation technique should also be defined, although it is doubtful if this technique will be applicable to measurements in the millimeter wave frequency range.

2. DEFICIENCIES IN REDUCING MEASUREMENT TECHNIQUES TO PRACTICE

Over the last two decades, a number of measurement techniques have evolved which could serve as viable alternates to current EMC/EMI measurement methods if reduced to practice. Some of these techniques are used extensively for other types of electromagnetic measurements; thus it is not the validity of the techniques but rather their use in satisfying EMC/EMI measurement objectives that is in question. For example, the compact range is commonly employed in performing antenna pattern, radar cross section, and other types of radiated measurements, and offers a distinct advantage as a radiated measurement technique in that it requires a relatively small test volume. As a second example, a statistical method for defining antenna gain characteristics was developed over twenty years ago. This method provides a means for defining antenna characteristics which is essentially independent of the site and which provides a realistic approach to assessing the performance of the antenna in an operational environment. The use of these two measurement techniques to satisfy EMI/EMC measurement requirements should be defined and reduced to practice (and reflected in appropriate standards).

The mode perturbation (tuned mode and stirred mode) measurement techniques were developed specifically for performing radiated EMC/EMI type measurements in shielded enclosures. The tuned mode enclosure was initially developed as a means of performing shielding effectiveness measurements, but later investigations were performed to extend its applicability to radiated emission and susceptibility measurements. Procedures for utilizing both the tuned mode and stirred mode enclosures have been investigated and are documented in the literature. However, there are still questions regarding the correlation between results obtained with mode perturbation techniques and those obtained with more conventional radiated measurement methods. These questions must be answered before the mode perturbation techniques can be reduced to practice and recommended as alternate measurement methods.

3. DEFICIENCIES IN CORRELATION AND UTILIZATION OF MEASUREMENT RESULTS

The utility of a particular measurement technique is relatively easy to define in terms of such parameters as frequency range, size of unit to be tested, cost of measurement technique, etc. What is not known, and what cannot be easily assessed from current knowledge of the various radiated measurement techniques, is how to correlate the measurement results obtained with different measurement techniques, or how to translate measurement results to a field environment. For example, suppose the tuned mode enclosure was employed to measure the susceptibility of a particular equipment. Since this measurement technique "immerses" the equipment in a fairly complex exposure field, how would the measurement results compare with results obtained with a different measurement technique? Moreover, how would the results be used to identify the potential susceptibility of the equipment in a field environment characterized by "plane wave" interference signals? Similar questions related to the correlation and utilization of measurement data were raised in Section 2. These questions indicate a serious deficiency in the current state-of-the-art of EMC/EMI measurement methodology -- a lack of understanding of the meaning, proper utilization, and correlation of measurement results obtained with the various measurement methods. It is felt that this deficiency overshadows individual problems related to specific measurement techniques, and its resolution is considered fundamental to the improvement or advancement of EMC/EMI measurement methods.

5.3 Deficiencies in MIL-STD-462 Measurement Philosophy

From a conceptual viewpoint, the development and use of a measurement standard to limit the radiated EMC/EMI characteristics of individual equipments is a valid approach to the control of field interference problems, even when the imposed limits are not related to a particular operating environment. Certainly, an equipment which meets specified emission and susceptibility limits is less likely to experience or cause interference when deployed in any environment than an equipment which does not meet these limits. In this respect, the MIL-STD-460 series plays an important role in achieving a system design which is electromagnetically compatible with its operating environment.

In practice, the above concept has a number of deficiencies. One deficiency is the lack of correlation between results obtained with different measurement techniques. A system could pass or fail its EMC/EMI test limit depending upon the measurement technique employed. A second deficiency is the inability to accurately assess the compatibility of a system with its operating environment from measurements performed under MIL-STD-462. It might be argued that the intent of the standard is only to insure that design limits have been met, and not to provide data for EMC prediction and analysis purposes. However, it appears illogical to state that measurements of a system's EMC/EMI characteristics are not relatable to its operation when deployed. If such a relationship does not exist, or cannot be established, then the value of the standards is highly questionable.

The above deficiencies lead to a third shortcoming; the fact that the concept of using the standards only to test EMC design limits does not maximize the utilization of the standards. It is considered grossly inefficient to encumber the time and costs of performing EMC/EMI measurements under MIL-STD-462, and then have to perform additional measurements (i.e., MIL-STD-449) to determine if a system will perform satisfactorily when deployed.

Any actions which are taken to improve or upgrade MIL-STD-462 techniques for performing radiated emission and susceptibility measurements should also address the above deficiencies, which are more philosophical than technical in nature. What is needed is not simply a revision of, or addition to, those measurement techniques which currently exist. Rather, a review and update of the overall measurement philosophy and approach to performing radiated measurements is needed to ensure that the measurement techniques employed and the measurement results obtained have maximum applicability to the EMI control of operational systems. This effort should also include a study of the test limits imposed by the standards to ensure that these limits reflect the state-of-the-art in system EMC/EMI design and in EMC/EMI measurement technology.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From the results of this program, it is concluded that a number of measurement techniques offer the potential of serving as viable alternates to those measurement techniques currently employed to satsify the measurement requirements of MIL-STD-462. However, many of these alternate techniques have as yet not been reduced to practice. A more significant conclusion which is drawn from the program activities and results is that serious deficiencies exist in current EMC/EMI radiated measurement methodologies. These deficiencies include shortcomings in current measurement techniques as well as problems with the overall measurement philosophy dictated by MIL-STD-462.

Shortcomings in current measurement techniques include (1) deficiencies which prevent the maximum utilization of available measurement techniques, (2) deficiencies in reducing to practice those measurement techniques which have been identified as possible alternates to current techniques, and (3) deficiencies related to the lack of correlation of measurement results obtained with different techniques.

From a conceptual or philosophical viewpoint, the MIL-STD-460 series is considered inadequate for practical system EMC control. The use of these standards to ensure that system EMC design limits have been met is questionable since different results can be obtained with different measurement techniques. The inability to relate the measurement results obtained under these standards to the EMC potential of a deployed system represents a relatively ineffective and costly underutilization of the standards.

6.2 Recommendations

It is recommended that actions be taken to improve and reduce to practice those measurement techniques which are applicable to the conduct of radiated emission and susceptibility measurements. In conjunction with these actions, a review and update of the overall measurement philosophy and approach to performing radiated measurements should be undertaken to ensure that the measurement techniques employed and the results obtained have maximum applicability to the EMI control of operational systems. Measurement limits to be dictated by the standards should also be reviewed to ensure that these limits conform to the state-of-the-art in EMC/EMI design techniques and in EMC/EMI instrumentation capabilities.

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